ONR Announcement # N00014-19-S-F005 Amendment 0001
ARO Announcement # W911NF-19-S-0008 Amendment 0001
AFOSR Announcement # FOA-AFRL-AFOSR-2019-0002

Fiscal Year (FY) 2020 Department of Defense Multidisciplinary Research Program of the University Research Initiative

The purpose of this amendment is to add language regarding opportunities to attract Australian funding for proposals with Australian collaborators. This can be found in Section 1. INTRODUCTION, and described in further detail in Topic 11. This amendment hereby replaces all previous postings of N00014-19-S-F005.

The purpose of this amendment is also to add language applying to ARMY SUBMISSIONS ONLY providing for the addition of cooperative agreements. This can be found in Section II. DETAILED INFORMATION ABOUT THE RESEARCH OPPORTUNITY and described in further detail in B. Federal Award Information Section. This amendment hereby replaces all previous postings of W911NF-19-S-0008.

Deadlines

White Paper Inquiries and Questions
24 May 2019 (Friday)

White Papers must be received no later than
03 June 2019 (Monday) at 11:59 PM Eastern Time

Application Inquiries and Questions
30 August 2019 (Friday)

Applications must be received no later than
13 September 2019 (Friday) at 11:59 PM Eastern Time

Special Note

Applications must be 'VALIDATED' by Grants.gov by the application deadline which can take up to 48 hours after successful submission.

See Timely Receipt Requirements and Proof of Timely Submission, b. Proposal Receipt Notices

Table of Contents

I. INTRODUCTION

This publication constitutes a Funding Opportunity Announcement (FOA) as contemplated in the Department of Defense Grants and Agreements Regulations (DoDGARS) 32 CFR 22.315(a). A formal Request for Proposals (RFP), solicitation, and/or additional information regarding this announcement will not be issued.

The Department of Defense (DoD) Multidisciplinary University Research Initiative (MURI), one element of the University Research Initiative (URI), is sponsored by the DoD research offices. Those offices include the Office of Naval Research (ONR), the Army Research Office (ARO), and the Air Force Office of Scientific Research (AFOSR) (hereafter collectively referred to as "DoD agencies").

DOD's MURI program addresses high risk basic research and attempts to understand or achieve something that has never been done before. The program was initiated over 25 years ago and it has regularly produced significant scientific breakthroughs with far reaching consequences to the fields of science, economic growth, and revolutionary new military technologies. Key to the program's success is the close management of the MURI projects by Service program officers and their active role in providing research guidance.

The DoD agencies will not issue paper copies of this announcement. The DoD agencies involved in this program reserve the right to select for award all, some or none of the proposals submitted in response to this announcement. The DoD agencies provide no funding for direct reimbursement of proposal development costs. Technical and cost proposals (or any other material) submitted in response to this FOA will not be returned. It is the policy of the DoD agencies to treat all proposals as competition sensitive information and to disclose their contents only for the purposes of evaluation.

Awards will take the form of grants and/or cooperative agreements (ARMY SUBMISSION ONLY). Any assistance instrument awarded under this announcement will be governed by the award terms and conditions that conform to DoD's implementation of the Office of Management and Budget (OMB) circulars applicable to financial assistance. Terms and conditions will reflect DoD implementation of OMB guidance in 2 CFR Part 200, "Uniform Administrative Requirements, Cost Principles, and Audit Requirements for Federal Awards."

Please note the following important items:

- A project abstract is required with the application and must be publically releasable as specified in the following section of this FOA: Section II. D. 2. b.(2)
- Responses to the Certifications and Representations indicated in Section II. H., 2 thru 4 of this FOA are required with the application.
- The notice that advisors external to the U.S. government may be used as subject-matter-expert technical consultants in the evaluation of the proposals after signing non-disclosure statements is contained in Section II. E. 4.
- Opportunities to attract Australian funding for proposals with Australian collaborators in Topic 11 are described at http://www.business.gov.au/ausmuri.

A. OVERVIEW

1. Federal Awarding Agency Names

Office of Naval Research
One Liberty Center
875 N. Randolph Street
Arlington, VA 22203-1995

Army Research Office
800 Park Office Drive
Research Triangle Park, NC 27709

Air Force Office of Scientific Research
875 North Randolph Street
Arlington, VA 22203

2. Funding Opportunity Title

Fiscal Year (FY) 2020 Department of Defense Multidisciplinary Research Program of the University Research Initiative

3. Announcement Type

Initial Announcement

4. Funding Opportunity Number

ONR: N00014-19-S-F005
ARO: W911NF-19-S-0008
AFOSR: FOA-AFRL-AFOSR-2019-0002

5. Catalog of Federal Domestic Assistance (CFDA) Numbers

ONR: 12.300
ARO: 12.431
AFOSR: 12.800

NOTE: Correct CFDA Number must be used in proposal submission to avoid misrouting.

6. Key Dates

White Papers due: 03 June 2019 (Monday) at 11:59 PM Eastern Time
Applications due: 13 September 2019 (Friday) at 11:59 PM Eastern Time

For a full Table of Events, see Section II. D. 4. "Significant Dates and Times"

II. DETAILED INFORMATION ABOUT THE RESEARCH OPPORTUNITY

A. PROGRAM DESCRIPTION

The MURI program supports basic research in science and engineering at U.S. institutions of higher education (hereafter referred to as "universities") that is of potential interest to DoD. The program is focused on multidisciplinary research efforts where more than one traditional discipline interacts to provide rapid advances in scientific areas of interest to the DoD. As defined in the DoD Financial Management Regulation:

> Basic research is systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications towards processes or products in mind. It includes all scientific study and experimentation directed toward increasing fundamental knowledge and understanding in those fields of the physical, engineering, environmental, and life sciences related to long-term national security needs. It is farsighted high payoff research that provides the basis for technological progress (DoD 7000.14-R, vol. 2B, chap. 5, para. 050201.B).

DoD's basic research program invests broadly in many fields to ensure that it has early cognizance of new scientific knowledge.

The FY 2020 MURI competition is for the topics listed below.

Detailed descriptions of the topics and the Topic Chief for each can be found in Section II. I, entitled, "SPECIFIC MURI TOPICS," The detailed descriptions are intended to provide the applicant a frame of reference and are not meant to be restrictive to the possible approaches to achieving the goals of the topic and the program. Innovative ideas addressing these research topics are highly encouraged.

Proposals from a team of university investigators are warranted when the necessary expertise in addressing the multiple facets of the topics may reside in different universities, or in different departments in the same university. By supporting multidisciplinary teams, the program is complementary to other DoD basic research programs that support university research through single-investigator awards. Proposals shall name one Principal Investigator (PI) as the responsible technical point of contact. Similarly, one institution shall be the primary awardee for the purpose of award execution. The PI shall come from the primary institution. The relationship among participating institutions and their respective roles, as well as the apportionment of funds including sub-awards, if any, shall be described in both the proposal text and the budget.

White papers and proposals addressing the following topics should be submitted to the Office of Naval Research (ONR):

ONR:

Topic 1: Stimuli-Responsive Materials based on Triggered Polymer Depolymerization

Topic 2: Quantum Benefits without Quantum Fragility: The Classical Entanglement of Light

Topic 3: Mathematical Methods for Deep Learning

Topic 4: Spin and Orbital Angular Momentum (SAM & OAM)

Topic 5: Photonic High-Order Topological Insulators (PHOTIs)

Topic 6: Active Topological Mechanical Metamaterials

Topic 7: Harvesting Oxygen from the Ocean

Topic 8: Exploring Oxidation and Surface Phenomena of Multi-Principal Element Alloys

Topic 9: The Physics of High-Speed Multiphase-flow / Material Interactions

Topic 10: Combining Disparate Environmental Data Into a Common Framework

White papers and proposals addressing the following topics should be submitted to the Army Research Office (ARO):

ARO:

Topic 11: Adaptive and Adversarial Machine Learning

Topic 12: Axion Electrodynamics beyond Maxwell's Equations

Topic 13: Engineering Endosymbionts to Produce Novel Functional Materials

Topic 14: Information Exchange Network Dynamics

Topic 15: Mathematical Intelligence: Machines with More Fundamental Capabilities

Topic 16: Quantum State Engineering for Enhanced Metrology

Topic 17: Solution Electrochemistry without Electrodes

Topic 18: Stimuli-Responsive Mechanical Metamaterials

White papers and proposals addressing the following topics should be submitted to the Air Force Office of Scientific Research (AFOSR):

AFOSR:

Topic 19: Machine Learning and Physics-Based Modeling and Simulation

Topic 20: Fundamental Design Principles for Engineering Orthogonal Liquid-Liquid Phase Separations in Living Cells

Topic 21: Modeling, Prediction, and Mitigation of Rare and Extreme Events in Complex Physical Systems

Topic 22: Fundamental Limits of Controllable Waveform Diversity at High Power

Topic 23: Full Quantum State Control at Single Molecule Levels

Topic 24: Constructive Mathematics and Its Synthetic Concepts from Type Theory

Topic 25: Weyl Fermion Optoelectronics

Topic 26: Mechanisms of Ice Nucleation and Anti-Icing Constructs

B. FEDERAL AWARD INFORMATION

1. Period of Performance

It is anticipated that the awards will be made in the form of grants (and cooperative agreements FOR ARMY SUBMISSIONS ONLY) to universities. The awards will be made at funding levels commensurate with the proposed research and in response to agency missions. Each individual award will be for a three-year base period with one two-year option period to bring the total maximum term of the award to five years. The base and option period, if exercised, will be incrementally funded.

2. Award Amount

The total amount of funding for the five years available for grants resulting from this MURI FOA is estimated to be approximately $180 million dollars pending out-year appropriations. MURI awards are contingent on availability of funds, the specific topic, and the scope of the proposed work. Typical annual funding per grant is in the $1.25M to $1.5M range. The amount of the award and the number of supported researchers should generally not exceed the limit specified for the individual topics in Section II. I.

It is strongly recommended that applicants communicate with the Research Topic Chiefs regarding these issues before the submission of formal proposals. Depending on the results of the proposal evaluation, there is no guarantee that any of the proposals submitted in response to a particular topic will be recommended for funding. On the other hand, more than one proposal may be recommended for funding for a particular topic.

C. ELIGIBILITY INFORMATION

This MURI competition is open only to, and proposals are to be submitted only by, U.S. institutions of higher education (universities) with degree-granting programs in science and/or engineering, including DoD institutions of higher education. To the extent that it is a part of a U.S. institution of higher education and is not designated as a Federally Funded Research and Development Center (FFRDC), a University Affiliated Research Center (UARC) or other University Affiliated Laboratory (UAL) is eligible to submit a proposal to this MURI competition and/or receive MURI funds. Ineligible organizations (e.g., industry, DoD laboratories, FFRDCs, and foreign entities) may collaborate on the research but may not receive MURI funds directly or via subaward.

When additional funding for an ineligible organization is necessary to make the proposed collaboration possible, such funds may be identified via a separate proposal from that organization. This supplemental proposal shall be attached to the primary MURI proposal and will be evaluated in accordance with the MURI review criteria by the responsible Research Topic Chief. If approved, the supplemental proposal may be funded using non-MURI or non-Government funds.

D. APPLICATION AND SUBMISSION INFORMATION

1. Application and Submission Process

Regardless of whether or not a non-MURI funded collaboration is included in the proposal, the same submission process for white papers and proposals will be followed.

The proposal submission process has two stages:

- Applicants are encouraged to submit a white paper; and
- Applicants must submit a proposal through Grants.gov.

Prospective awardees are encouraged to submit white papers to minimize the labor and cost associated with the production of detailed proposals that have very little chance of being selected for funding. Based on an assessment of the white papers, the responsible Research Topic Chief will provide informal feedback notification to the prospective awardees to encourage or discourage submission of proposals. The Research Topic Chief may also on occasion, provide feedback encouraging re-teaming to strengthen a proposal.

Submission of White Papers: White papers may be submitted via e-mail directly to a Research Topic Chief, via the United States Postal Service (USPS), or via a commercial carrier to the agency specified for the topic. For hard copy submissions, use the addresses provided in Section II. D. 2. a, entitled, "Address for Submission of Hard Copy White Papers."

White papers should be stapled in the upper left hand corner; plastic covers or binders should not be used. Separate attachments, such as individual brochures or reprints, will not be accepted. **Do NOT email ZIP files and/or password protected files.**

White Paper Deadline: The due date and time for receipt of white papers is no later than 03 June 2019 (Monday) at 11:59 PM Eastern Time.

Evaluation/Notification: Initial evaluations of the white papers will be issued on, or about, 19 June 2019 (Wednesday).

Submission of Proposal: Any applicant may submit a proposal even if its white paper was not identified as being of "particular value" to the Government or if no white paper was submitted.

However, the initial evaluation of the white papers should give the prospective awardee some indication of whether a proposal would likely result in an award.

Proposal Deadline: Proposals must be submitted and received electronically through Grants.gov not later than 13 September 2019 (Friday) at 11:59 PM Eastern Time to be considered for selection. This is the final due date.

Applicants are responsible for making sure the application is submitted, received, and validated by Grants.gov before the application deadline. Late applications are ineligible for consideration.

Award Notification: It is anticipated that final selections for award will be made on or about, 01 February 2020 (Friday). See Section II. D. 4. for "Significant Dates and Times."

2. Content and Format of White Papers/Applications

The white papers and proposals submitted under this FOA are expected to address unclassified basic research. White papers and proposals will be protected from unauthorized disclosure in accordance with applicable laws and DoD regulations.

Applicants are expected to appropriately mark each page of their submission that contains proprietary information.

For proposals containing data that the applicant does not want disclosed to the public for any reason, or used by the Government except for evaluation purposes, the applicant shall mark the title page with the following legend:

"This proposal includes data that shall not be disclosed outside the Government and shall not be duplicated, used, or disclosed--in whole or in part--for any purpose other than to evaluate the proposal or for program coordination. If, however, a grant is awarded to this applicant as a result of--or in connection with-- the submission of this data, the Government shall have the right to duplicate, use, or disclose the data to the extent provided in the resulting award. This restriction does not limit the Government's right to use information contained in this data if it is obtained from another source without restriction. The data subject to this restriction is contained in (insert numbers or other identification of sheets)."

Also, mark each sheet of data that the applicant wishes to restrict with the following legend: "Use or disclosure of data contained on this sheet is subject to the restriction on the title page of this proposal."

Titles given to the White Papers/Proposals should be descriptive of the basic research they cover and not be merely a copy of the topic title.

Use of Principal Investigator (PI) Over Multiple Proposals/Topics:

Applicants contemplating the use of an individual as Principal Investigator (PI) for more than one proposal and/or topic are strongly encouraged to contact the Topic Chief(s) prior to white paper submission to determine if the Topic Chief(s) support PI participation in multiple proposals and/or topics. Support of the use of a PI over multiple proposals and/or topics is at the discretion of the Topic Chief(s).

PI participation in multiple proposals and/or topics shall be identified in all white paper submissions where the PI is proposed. The white paper should also document the amount of time the PI is available for the project(s) and how the PI will manage their time given the possibility of multiple awards.

Applicants that do not submit white papers, but wish to submit a proposal, shall document PI participation in multiple proposals and/or topics in all proposals where the PI is proposed. The proposal should also document the amount of time the PI is available for the project(s) and how the PI will manage their time given the possibility of multiple awards.

a. White Papers

White paper format shall be as follows:

- Paper Size - 8.5 x 11 inch paper
- Margins - 1 inch
- Spacing – single spaced
- Font - Times New Roman, 12 point
- Number of Pages - no more than four (4) single-sided pages (excluding cover letter, cover page, and curriculum vitae). White paper pages beyond the 4-page limit may not be evaluated or read.
- Copies - For Hard Copy Submissions please provide one (1) original and two (2) copies.

White Paper content shall be as follows:

- A cover letter (optional – one page)
- A cover page, labeled "PROPOSAL WHITE PAPER," that includes the FOA number, proposed title, and proposer's technical point of contact, with telephone number, facsimile number, e-mail address, topic number, and topic title
- Identification of the research and issues
- Proposed technical approaches
- Potential impact on DoD capabilities
- Potential team and management plan
- Summary of estimated costs
- Curriculum vitae of key investigators (see Use of Principal Investigator (PI) Over Multiple Proposals/Topics)
- Identification of any Organizational Conflict(s) of Interest (if any) – See Section II. H. 5 for more details.
- Identification of anticipated human or animal subject research

The white paper should provide sufficient information on the research being proposed (e.g., hypothesis, theories, concepts, approaches, data measurements and analysis, etc.) to allow for an assessment by a technical expert. It is not necessary for white papers to carry official institutional signatures.

Address for Submission of Hard Copy White Papers

Each topic in this announcement has one or more Research Topic Chief(s) identified from one of the participating agencies; ONR, ARO, or AFOSR. Prospective applicants shall submit the white paper to one of the Research Topic Chiefs at the agency to which they are applying.

Submission of hard copy white papers shall be sent to the addresses below.
Important Notes Regarding Submission of Hard Copy White Papers: If the Applicant is using USPS, please allow an additional five (5) business days for the package to be delivered due to USPS mail being sent to a central location for special processing before it is sent to the addresses below.

Office of Naval Research:
Hard copies of white papers topics (1) through (10) should be sent to the Office of Naval Research at the following address: (For those topics with multiple topic chiefs, send the white paper to the first topic chief listed.)

Primary:
Office of Naval Research
ATTN: (list name of responsible Research Topic Chief)
875 North Randolph Street - Suite W256A
Arlington, VA 22203-1995
Point of Contact: Paula Barden
Email: paula.barden.ctr@navy.mil
703-696-4111

Secondary:
Office of Naval Research
ATTN: (list name of responsible Research Topic Chief)
875 North Randolph Street - Suite 1020
Arlington, VA 22203-1995
Point of Contact: Dr. Ellen Livingston
Email: ellen.s.livingston@navy.mil
Phone: 703-696-4668

U.S. Army Research Office:
Hard copy white papers addressing topics (11) through (18) should be sent to the U.S. Army Research Office at one of the following addresses:

For delivery by USPS use:
U.S. Army Research Office (FY20 MURI)
P. O. Box 12211
Research Triangle Park, NC 27709-2211

For commercial delivery (such as FedEx, UPS, etc.) use:
U.S. Army Research Office (FY20 MURI)
For white papers include:
ATTN: (list name of responsible Research Topic Chief)
800 Park Office Drive, Suite 4229
Research Triangle Park, NC 27709
919-549-4211

Air Force Office of Scientific Research:
Hard copy white papers addressing topics (19) through (26) should be sent to the Air Force Office of Scientific Research at the following address:

Air Force Office of Scientific Research
ATTN: (list name of responsible Research Topic Chief)
875 North Randolph Street, Suite 325, Room 3112
Arlington, VA 22203-1768
Reference phone # 703-696-9544
Email: MURI@us.af.mil

b. Application Package

NOTE: Proposals must be submitted electronically through Grants.gov.

Before you start: Identify the SPECIFIC MURI TOPICS to which you are proposing and obtain the associated agency and Topic Chief for your topic. You will find the topics with the associated agency and Topic Chief listed in Section II. I, entitled "SPECIFIC MURI TOPICS". This information is needed for the grants.gov Agency Routing Identifier and the CFDA number.

Content and Form of Application:

Prospective applicants submitting an application must complete the mandatory forms in accordance with the instructions provided on the forms and the additional instructions below. Files that are attached to the forms must be in Adobe Portable Document Format (.pdf) unless otherwise specified in this announcement.

Required Forms

(1) SF 424 Form (RESEARCH & RELATED) (Mandatory)

The SF 424 (R&R) form must be used as the cover page for all proposals. Complete all required fields in accordance with the "pop-up" instructions on the form and the following instructions for specific fields. Please complete the SF 424 first, as some fields on the SF 424 are used to auto-populate fields on other forms.

The completion of most fields is self-explanatory with the exception of the following special instructions:

- Field 3 - Date Received by State: The Date Received by State and the State Application Identifier are not applicable to research. Leave blank.

- Field 4a - Federal Identifier:
  For ONR, enter "N00014"
  For ARO, enter "W36QYT"
  For AFOSR, enter "FA9550"

- Field 4b - Agency Routing Number:

  For ONR, Enter the three (3) digit Research Topic Chief's Code and the Research Topic Chief's name (last name first) in brackets (e.g., 331 [Smith, John]).
  For ARO, enter the name of the Research Topic Chief.
  For AFOSR, enter the Research Topic Chief's Topic Number (#) and Research Topic Chief's name (last name first) in brackets (e.g., 12 [Smith, John]).

Applicants who fail to provide an Agency Routing Number may receive a notice that their proposal is rejected.

- Field 4c - Previous Grants.gov Tracking ID: If this submission is for a Changed/Corrected Application, enter the Grants.gov tracking number of the previous proposal submission; otherwise, leave blank.

- Field 7 - Type of Applicant: Complete as indicated. If the organization is a Minority Institution, select "Other" and under "Other (Specify)" note that the institution is a Minority Institution (MI).

- Field 9 - Name of Federal Agency: List the appropriate agency (i.e., ONR, AFOSR, or ARO) as the reviewing agency. This field is usually pre-populated in Grants.gov.

- Field 16 - Is Application Subject to Review by State Executive Order 12372 Process? Choose "No". Check "Program is Not Covered by Executive Order 12372."

- Field 17 – Certification: All awards require some form of certifications of compliance with national policy requirements. By checking the "I agree" box in field 17, and attaching the representation to Field 18 of the SF424 (R&R) as part of the electronic proposal submitted via Grants.gov, the Grant Applicant is providing the certification on lobbying required by 32 CFR Part 28 and representation regarding an unpaid delinquent tax liability or a felony conviction under any federal law – DoD appropriations.

(2) R&R Form: Project Abstract Form (Mandatory)

The project summary/abstract must identify the research problem and objectives, technical approaches, anticipated outcome of the research, if successful, and impact on DoD capabilities. Use only characters available on a standard QWERTY keyboard. Spell out all Greek letters, other non-English letters, and symbols. Graphics are not allowed and there is a 4,000 character limit including spaces.

Do not include proprietary or confidential information. The project summary abstract must be marked by the applicant as "Approved for Public Release". Abstracts of all funded research projects will be posted on the public DTIC website: https://dodgrantawards.dtic.mil/grants

(3) R&R Form: Research and Related Other Project Information (Mandatory)

- Fields 1 and 1a - Human Subject Use: Each proposal must address human subject involvement in the research by completing Fields 1 and 1a of the R&R Other Project Information form. For proposals containing activities that include or may include "research involving human subjects" as defined in DoDI 3216.02, prior to award, the Applicant must submit the documentation under "Use of Human Subjects in Research" (Section II. H. 6.).

- Fields 2 and 2a – Vertebrae Animal Use: Each proposal must address animal use protocols by completing Fields 2 and 2a of the R&R Other Project Information form. If animals are to be utilized in the research effort proposed, the Applicant must submit the documents described under "Use of Animals" (Section II. H. 6.).

- Fields 4a through 4d - Environmental Compliance: Address these fields and briefly indicate whether the intended research will result in environmental impacts outside the laboratory, and how the applicant will ensure compliance with environmental statutes and regulations.

  Federal agencies making grant or cooperative agreement awards and recipients of such awards must comply with various environmental requirements. The National Environmental Policy Act of 1969 (NEPA), 42 U.S.C. Sections 4321-4370 (a), requires that agencies consider the environmental impact of "major Federal actions" prior to any final agency decision. With respect to those awards which constitute "major Federal actions," as defined in 40 CFR 1508.18, federal agencies may be required to comply with NEPA and prepare an environmental impact statement (EIS), even if the agency does no more than provide grant funds to the recipient. Questions regarding NEPA compliance should be referred to the Research Topic Chief.

- Field 7 – Project Abstract: Leave Field 7 blank; complete Form SF 424, Project Abstract.

- Field 8 – Project Narrative: Describe clearly the research, including the objective and approach to be performed, keeping in mind the evaluation criteria. Attach the entire proposal narrative to R&R Other Project Information form in Field 8. To attach a Project Narrative in Field 8 click on "Add Attachment" and attach the technical proposal as a single PDF file. (Save the file as "Technical Proposal," as typing in the box is prohibited).

The Following Formatting Rules Apply for Field 8

- Paper size when printed - 8.5 x 11-inch paper
- Margins - 1 inch
- Spacing - single
- Font - Times New Roman, 12 point
- Number of pages in Field 8 - no more than twenty-five (25) single-sided pages. The cover page, table of contents, list of references, letters of support, curriculum vitae and list of on-going and pending research support are excluded from the page limitations. The pages of proposals exceeding the page limit may not be included in the evaluation.

Requirements for Field 8

The first page (cover page) of the narrative must include the following information:

- Principal Investigator (PI) name
- Phone number, fax number and e-mail address
- Institution, Department, Division
- Institution address
- Other universities involved in the MURI team
- Is the PI a current DoD Contractor or Grantee?
- If yes, provide Agency, point of contact; and phone number.
- Proposal title
- Institution proposal number
- Agency to which proposal is submitted
- Topic number and topic title

Table of Contents: List project narrative sections and corresponding page numbers.

Technical Approach: Describe in detail the basic research in science and/or engineering to be undertaken. State the objective and approach, including how data will be analyzed and interpreted. Discuss the relationship of the proposed research to the state-of-the-art knowledge in the field and to related efforts in programs elsewhere, and discuss potential scientific breakthroughs. Include appropriate literature citations/references. Discuss the nature of expected results. Describe plans for the research training of students. Include the number of time equivalent graduate students and undergraduates, if any, to be supported each year. Discuss the involvement of other students, if any.

Project Schedule: A summary of the schedule of events and a detailed description of the expected results.

Management Approach:

• A discussion of the overall approach to the management of this effort, including brief discussions of: required facilities; relationships with any subawardees and with other organizations; availability of personnel; and planning, scheduling and control procedures.

• Describe the facilities available for the accomplishment of the proposed research and related education objectives. Describe any capital equipment planned for acquisition under this program and its application to the proposed research. If possible, budget for capital equipment should be allocated to the first budget period of the grant. Include a description of any government furnished equipment/ hardware/ software/ information, that are required for the proposed effort.

• Describe in detail proposed subawards to other eligible universities or with other eligible institutions. If subawards to other universities are proposed, make clear the division of research activities, to be supported by detailed budgets for the proposed subawards.

• Designate one individual as the Principal Investigator for the award, for the purpose of technical responsibility and to serve as the primary point of contact with an agency's Research Topic Chief. Briefly summarize the qualifications of the Principal Investigator and other key investigators who will conduct the proposed research. Details can be included in the individual CVs.

• Briefly describe the research activities of the Principal Investigator (PI) and co-investigators in on-going and pending research projects, the time charged to each of these projects, and their relationship to the proposed effort. Details should be included in the individual CVs. Provide the percentage of the PI's time which will be allotted to this research project by year and the percentage of his time which is specifically committed or obligated to other activities (e.g. teaching, other grants, contracts, consultancies).

• Describe plans to manage the interactions among members of the proposed research team.

• Identify other parties to whom the proposal has been, or will be sent, including agency contact information.

List of References: List publications cited in above sections.

Letters of Support: Up to five Letters of Support, describing interest in the topic area expressing a commitment for funding support may be included.

Curriculum Vitae: Include curriculum vitae of the Principal Investigator and key co-investigators. List the amount of funding and describe the research activities of the Principal Investigator and key co-investigators in on-going and pending research projects, whether or not acting as Principal Investigator in these other projects.

(4) R&R Form: Research & Related Budget

The applicant must use the Grants.gov forms from the application package template associated with the FOA on the Grants.gov web site located at https://www.grants.gov/.

A separate Adobe .pdf document should be included in the application that provides appropriate justification and/or supporting documentation for each element of cost proposed. This document shall be attached under Section K. "Budget Justification" of the Research and Related Budget form. Click "Add Attachment" to attach.

Budget format should be as follows:

- Paper Size – 8.5 x 11-inch paper
- Margins – 1 inch
- Spacing – single spaced
- Font – Times New Roman, 12 point
- There are no page limitations to the Budget.

NOTE: The electronic file name for all documents submitted under this FOA must not exceed 68 characters in length, including the file name extension.

The budget shall adhere to the following guidelines.

There should be a detailed breakdown of all costs, by cost category, and by the calendar periods stated below. For budget purposes, use an award start date of 01 May 2020. Note that the budget for each of the calendar periods below should include only those costs to be expended during that calendar period. The budget should also include an option for two additional years

For proposals to **<u>ONR topics</u>**, the Recommended Funding Profile is:

(1) FY20: Twelve months (01 May 20 to 30 Apr 21): $1,500,000
(2) FY21: Twelve months (01 May 21 to 30 Apr 22): $1,500,000
(3) FY22: Twelve months (01 May 22 to 30 Apr 23): $1,500,000

Three-year base subtotal: $4,500,000

(4) FY23: Twelve months (01 May 23 to 30 Apr 24): $1,500,000
(5) FY24: Twelve months (01 May 24 to 30 Apr 25): $1,500,000

Two-year option subtotal: $3,000,000
Five-year total: $7,500,000

For proposals to **<u>ARO topics</u>**, the Recommended Funding Profile is:

(1) FY20: Five months (01 May 20 to 30 Sep 20): $520,833
(2) FY21: Twelve months (01 Oct 20 to 30 Sep 21): $1,250,000
(3) FY22: Twelve months (01 Oct 21 to 30 Sep 22): $1,250,000
(4) FY23: Seven months (01 Oct 22 to 30 Apr 23): $729,167

Three-year base subtotal: $3,750,000

(4) FY23: Five months (01 May 23 to 30 Sep 23): $520,833
(5) FY24: Twelve months (01 Oct 23 to 30 Sep 24): $1,250,000

(6) FY25: Seven months (01 Oct 24 to 30 Apr 25): $729,167

Two-year option subtotal: $2,500,000
Five-year total: $6,250,000

For proposals to **AFOSR topics**, the Recommended Funding Profile is:

(1) FY20: Five months (01 May 20 to 30 Sep 20): $625,000
(2) FY21: Twelve months (01 Oct 20 to 30 Sep 21): $1,500,000
(3) FY22: Twelve months (01 Oct 21 to 30 Sep 22): $1,500,000
(4) FY23: Seven months (01 Oct 22 to 30 Apr 23): 875,000

Three-year base subtotal: $4,500,000

(4) FY23: Five months (01 May 23 to 30 Sep 23): $625,000
(5) FY24: Twelve months (01 Oct 23 to 30 Sep 24): $1,500,000
(6) FY25: Seven months (01 Oct 24 to 30 Apr 25): $875,000

Two-year option subtotal: $3,000,000
Five-year total: $7,500,000

Annual budget should be driven by program requirements. Elements of the budget should include:

- Direct Labor – Individual labor categories or persons, with associated labor hours and unburdened direct labor rates. Provide any escalation rates for out years.

- Administrative and Clerical Labor – Salaries of administrative and clerical staff are normally indirect costs (and included in an indirect cost rate). Direct charging of these costs may be appropriate when a major project requires an extensive amount of administrative or clerical support significantly greater than normal and routine levels of support. Budgets proposing direct charging of administrative or clerical salaries must be supported with a budget justification which adequately describes the major project and the administrative and/or clerical work to be performed.

- Fringe Benefits and Indirect Costs (F&A, Overhead, G&A, etc.) – The proposal should show the rates and calculation of the costs for each rate category. If the rates have been approved/negotiated by a Government agency, provide a copy of the memorandum/agreement. If the rates have not been approved/ negotiated, provide sufficient detail to enable a determination of allowability, allocability and reasonableness of the allocation bases, and how the rates are calculated. Additional information may be requested, if needed. If composite rates are used, provide the calculations used in deriving the composite rates.

- Travel – The proposed travel cost should include the following for each trip: the purpose of the trip, origin and destination if known, approximate duration, the number of travelers, and the estimated cost per trip must be justified based on the organizations historical average cost per trip or other reasonable basis for estimation. Such estimates and the resultant costs claimed must conform to the applicable Federal cost principals.

- Subawards/Subcontracts – Provide a description of the work to be performed by the subrecipient/ subcontractor. For each subaward, a detailed cost proposal is required to be submitted by the subrecipient(s). A proposal and supporting documentation must be received and reviewed before the Government can complete its cost analysis of the proposal and enter negotiations. The preferred method of receiving subcontract information is for this information to be included with the Prime's proposal; however, a subcontractor's cost proposal can be provided in a sealed envelope with the recipient's cost proposal or via e-mail directly to the Program Officer at the same time the prime proposal is submitted. The e-mail should identify the proposal title, the prime Applicant, and that the attached proposal is a subcontract. Fee/Profit guidance is noted below.

- Consultants – Provide a breakdown of the consultant's hours, the hourly rate proposed, any other proposed consultant costs, a copy of the signed Consulting Agreement or other documentation supporting the proposed consultant rate/cost, and a copy of the consultant's proposed statement of work, if it is not already separately identified in the prime awardee's proposal.

- Materials & Supplies – Provide an itemized list of all proposed materials and supplies including quantities, unit prices, and the basis for the estimate (e.g., quotes, prior purchases, catalog price lists)

- Recipient Acquired Equipment or Facilities – Equipment and/or facilities are normally furnished by the Recipient. If acquisition of equipment and/or facilities is proposed, a justification for the purchase of the items must be provided. Provide an itemized list of all equipment and/ or facilities costs and the basis for the estimate (e.g., quotes, prior purchases, catalog price lists). Allowable items normally would be limited to research equipment not already available for the project. General purpose equipment (i.e., equipment not used exclusively for research, scientific or other technical activities, such as personal computers, laptops, office equipment) should not be requested unless they will be used primarily or exclusively for the project. For computer/laptop purchases and other general purpose equipment, if proposed, include a statement indicating how each item of equipment will be integrated into the program or used as an integral part of the research effort.

- Other Direct Costs – Provide an itemized list of all remaining proposed other direct costs, such as Graduate Assistant tuition, laboratory fees, report and publication costs, and the basis for the estimate (e.g., quotes, prior purchases, catalog price lists).

- Fee Profit – Fee/profit is unallowable under assistance agreements at either the prime or subaward level but may be permitted on subcontracts issued by the prime awardee.

(5) R&R Form: Research & Related Personal Data (Mandatory)

This form will be used by DoD as the source of demographic information, such as gender, race, ethnicity, and disability information for the Project Director/Principal Investigator and all other persons identified as Co-Project Director(s)/Co-Principal Investigator(s). Each application must include this form with the name fields of the Project Director/Principal Investigator and any Co-Project Director(s)/Co-Principal Investigator(s) completed; however, provision of the demographic information in the form is voluntary. If completing the form for multiple individuals, each Co-Director/Co-Principal Investigator can be added by selecting the "Next Person" button. The demographic information, if provided, will be used for statistical purposes only and will not be made available to merit reviewers. Applicants who do not wish to provide some or all of the information should check or select the "Do not wish to provide" option.

NOTE: The Government Accountability Office, in its report GAO-16-14, WOMEN IN STEM RESEARCH: Better Data and Information Sharing Could Improve Oversight of Federal Grant-making and Title IX Compliance, December 3, 2015, recommended that the Department of Defense collect certain demographic and career information to be able to assess the success rates of women who are proposed for key roles in applications in science, technology, engineering, or mathematics disciplines.

3. Grants.gov Application Submission and Receipt Procedures

NOTE: White Papers must **not** be submitted through the Grants.gov application process.

How to Register to Apply through Grants.gov

a. *Instructions:* Applicants should read the registration instructions carefully and prepare the information requested before beginning the registration process. Reviewing and assembling the required information before beginning the registration process will alleviate last-minute searches for required information.

The registration process can take up to four weeks to complete. Therefore, registration should be done in sufficient time to ensure it does not impact your ability to meet required application submission deadlines.

If individual applicants are eligible to apply for this grant funding opportunity, refer to: https://www.grants.gov/web/grants/applicants/registration.html

Organization applicants can find complete instructions here: https://www.grants.gov/web/grants/applicants/organization-registration.html

(1) *Obtain a DUNS Number*: All entities applying for funding, including renewal funding, must have a Data Universal Numbering System (DUNS) number from Dun & Bradstreet (D&B). Applicants must enter the DUNS number in the data entry field labeled "Organizational DUNS" on the SF 424 form.

For more detailed instructions for obtaining a DUNS number, refer to: https://www.grants.gov/web/grants/applicants/organization-registration/step-1-obtain-duns-number.html

(2) *Register with SAM*: In addition to having a DUNS number, organizations applying online through Grants.gov must register with the System for Award Management (SAM).

All organizations must register with SAM in order to apply online. Failure to register with SAM will prevent your organization from applying through Grants.gov.

For more detailed instructions for registering with SAM, refer to: https://www.grants.gov/web/grants/applicants/organization-registration/step-2-register-with-sam.html

(3) *Create a Grants.gov Account*: The next step in the registration process is to create an account with Grants.gov. Applicants must know their organization's DUNS number to complete this process. Completing this process automatically triggers an email request for applicant roles to the organization's E-Business Point of Contact (EBiz POC) for review. The EBiz POC is a representative from your organization who is the contact listed for SAM. To apply for grants on behalf of your organization, you will need the Authorized Organizational Representative (AOR) role.

For more detailed instructions about creating a profile on Grants.gov, refer to: https://www.grants.gov/web/grants/applicants/registration/add-profile.html

(4) *Authorize Grants.gov Roles*: After creating an account on Grants.gov, the EBiz POC receives an email notifying them of your registration and request for roles. The EBiz POC will then log in to Grants.gov and authorize the appropriate roles, which may include the AOR role, thereby giving you permission to complete and submit applications on behalf of the organization. You will be able to submit your application online any time after you have been approved as an AOR.

For more detailed instructions about creating a profile on Grants.gov, refer to: https://www.grants.gov/web/grants/applicants/registration/authorize-roles.html

5) *Track Role Status*: To track your role request, refer to: https://www.grants.gov/web/grants/applicants/registration/track-role-status.html

b. *Electronic Signature*: When applications are submitted through Grants.gov, the name of the organization's AOR that submitted the application is inserted into the signature line of the application, serving as the electronic signature. The EBiz POC **must** authorize individuals who are able to make legally binding commitments on behalf of the organization as an AOR; **this step is often missed and it is crucial for valid and timely submissions.**

How to Submit an Application to ONR, ARO, or AFOSR via Grants.gov

Grants.gov applicants can apply online using Workspace. Workspace is a shared, online environment where members of a grant team may simultaneously access and edit different webforms within an application. For each funding opportunity announcement (FOA), you can create individual instances of a workspace.

Below is an overview of applying on Grants.gov. For access to complete instructions on how to apply for opportunities, refer to: https://www.grants.gov/web/grants/applicants/apply-for-grants.html

a. *Create a Workspace*: Creating a workspace allows you to complete it online and route it through your organization for review before submitting.

b. *Complete a Workspace*: Add participants to the workspace, complete all the required forms, and check for errors before submission.

1. *Adobe Reader*: If you decide not to apply by filling out web forms you can download individual PDF forms in Workspace so that they will appear similar to other Standard forms. The individual PDF forms can be downloaded and saved to your local device storage, network drive(s), or external drives, then accessed through Adobe Reader.

NOTE: Visit the Adobe Software Compatibility page on Grants.gov to download the appropriate version of the software at: https://www.grants.gov/web/grants/applicants/adobe-software-compatibility.html

2. *Mandatory Fields in Forms:* In the forms, you will note fields marked with an asterisk and a different background color. These fields are mandatory fields that must be completed to successfully submit your application.

3. *Complete SF 424 Fields First*: The forms are designed to fill in common required fields across other forms, such as the applicant name, address, and DUNS number. To trigger this feature, an applicant must complete the SF 424 information first. Once it is completed, the information will transfer to the other forms.

c. *Submit a Workspace*: An application may be submitted through workspace by clicking the Sign and Submit button on the Manage Workspace page, under the Forms tab. Grants.gov recommends submitting your application package at least 24-48 hours prior to the close date to provide you with time to correct any potential technical issues that may disrupt the application submission.

d. *Track a Workspace*: After successfully submitting a workspace package, a Grants.gov Tracking Number (GRANTXXXXXXXX) is automatically assigned to the package. The number will be listed on the Confirmation page that is generated after submission.

For additional training resources, including video tutorials, refer to: https://www.grants.gov/web/grants/applicants/applicant-training.html

Applicant Support: Grants.gov provides applicants 24/7 support via the toll-free number 1-800-518-4726 and email at support@grants.gov. For questions related to the specific grant opportunity, contact the number listed in the application package of the grant you are applying for.

If you are experiencing difficulties with your submission, it is best to call the Grants.gov Support Center and get a ticket number. The Support Center ticket number will assist the DoD agency with tracking your issue and understanding background information on the issue.

Timely Receipt Requirements and Proof of Timely Submission

a. *Online Submission.* All applications must be received by 11:59 pm Eastern time on the due date established. Proof of timely submission is automatically recorded by Grants.gov. An electronic date/time stamp is generated within the system when the application is successfully received by

Grants.gov. The applicant AOR will receive an acknowledgement of receipt and a tracking number (GRANTXXXXXXXX) from Grants.gov with the successful transmission of their application. Applicant AORs will also receive the official date/time stamp and Grants.gov Tracking number in an email serving as proof of their timely submission.

When the DoD agency successfully retrieves the application from Grants.gov, and acknowledges the download of submissions, Grants.gov will provide an electronic acknowledgment of receipt of the application to the email address of the applicant with the AOR role. Again, proof of timely submission shall be the official date and time that Grants.gov receives your application. Applications received by Grants.gov after the established due date for the program will be considered late and will not be considered for funding by the DoD agency.

Applicants using slow internet, such as dial-up connections, should be aware that transmission can take some time before Grants.gov receives your application. Again, Grants.gov will provide either an error or a successfully received transmission in the form of an email sent to the applicant with the AOR role. The Grants.gov Support Center reports that some applicants end the transmission because they think that nothing is occurring during the transmission process. Please be patient and give the system time to process the application.

b. *Proposal Receipt Notices*. After a proposal is submitted through Grants.gov, the Authorized Organization Representative (AOR) will receive a series of three emails. It is extremely important that the AOR watch for and save each of the emails. You will know that your proposal has reached the DoD agency when the AOR receives email Number 3. You will need the Submission Receipt Number (email Number 1) to track a submission. The three emails are:

Number 1 – The applicant will receive a confirmation page upon completing the submission to Grants.gov. This confirmation page is a record of the time and date stamp that is used to determine whether the proposal was submitted.

Number 2 – The applicant will receive an email indicating that the proposal has been **validated** by Grants.gov within two days of submission (This means that all of the required fields have been completed). After an institution submits an application, Grants.gov generates a submission receipt via email and also sets the application status to “Received.” This receipt verifies the Application has been successfully delivered to the Grants.gov system. Next, Grants.gov verifies the submission is valid by ensuring it does not contain viruses, the opportunity is still open, and the applicant login and applicant DUNS number match. If the submission is valid, Grants.gov generates a submission validation receipt via email and sets the application status to “Validated.” If the application is not validated, the application status is set to "Rejected." The system sends a rejection email notification to the institution, and the institution must resubmit the application package. Applicants can track the status of their application by logging in to Grants.gov.

Number 3 – The third notice is an acknowledgment of receipt in email form from ONR within ten days from the proposal due date, if applicable. The email is sent to the authorized representative for the institution. The email for proposals notes that the proposal has been received and provides the assigned tracking number.

4. Significant Dates and Times

Schedule of Events		
Event	**Date**	**Time**
Questions Regarding white papers*	24 May 2019 (Friday)	
White Papers Due	03 June 2019 (Monday)	11:59 PM Eastern Time
Notification of Evaluations of White Papers	19 June 2019 (Wednesday) **	
Questions Regarding Proposals*	30 August 2019 (Friday)	
Proposals Due	13 September 2019 (Friday)	11:59 PM Eastern Time
Notification of Selection for Award	01 February 2020 **	
Estimated start date of grant	01 May 2020 **	

* Questions submitted after the Q&A deadline as noted in the table above may not be answered. The due date for submission of the white paper and/or application will not be extended.

** These dates are estimates as of the date of this announcement.

Note: Due to changes in security procedures since September 11, 2001, the time required for hard-copy written materials to be received at any of the DoD Agencies has increased. Materials submitted through the U.S. Postal Service, for example, may take five days or more to be received, even when sent by Express Mail. Thus, any hard-copy white papers should be submitted in advance of the deadline established in the solicitation so that it will not be received late and thus be ineligible for consideration.

E. APPLICATION REVIEW INFORMATION

1. Evaluation Criteria

Basic Research: The MURI Program is funded by a basic research appropriation. White papers and proposals, in order to be considered for funding, are therefore required to be of a basic, rather than applied or advanced technological, nature.

Note that basic research includes "scientific study and experimentation directed toward increasing fundamental knowledge and understanding" while applied research deals with the development of "useful materials, devices, and systems or methods" and "the design, development, and improvement of prototypes and new processes to meet general mission area requirements.” The full definitions of these terms are contained in document: (DoD 7000.14-R, vol. 2B, chap. 5, para. 050201.B)

White papers will be evaluated to assess whether the proposed research is likely to meet the objectives of the specific topic, and thus whether to encourage the submission of a proposal. The assessment of the white papers will primarily focus on scientific and technical merits, potential for the research to significantly advance fundamental understanding in the topic area, and potential DoD interest.

Proposals responding to this FOA in each topic area will be evaluated using the following criteria:

- Scientific and technical merits of the proposed basic science and/or engineering research;
- Potential for the research, if successful, to significantly advance fundamental understanding in the topic area;
- Potential DoD relevance and contribution to the Department of Defense mission;
- Qualifications and availability of the Principal Investigator and other investigators;
- Adequacy of current or planned facilities and equipment to accomplish the research objectives;
- Impact of interactions with other organizations engaged in related research and development, in particular DoD laboratories, industry, and other organizations that perform research and development for defense applications; and
- Realism and reasonableness of cost (cost sharing is not a factor in the evaluation)

The Government will evaluate options for award purposes by adding the total cost for all options to the total cost for the basic requirement. Evaluation of options will not obligate the Government to exercise the options during grant performance.

2. Review and Selection Process

The ultimate recommendation for award of proposals is made by the DoD’s scientific/technical community. Recommended proposals will then be forwarded to ONR, AFOSR, or ARO Contracts and Grant Awards Management office. Any notification received from the DoD agency that indicates that the Applicant’s proposal has been recommended does not ultimately guarantee an award will be made. This notice indicates that the proposal has been selected in accordance with the evaluation criteria stated above and has been sent to the Grants Department to conduct cost analysis, determine the Applicant's responsibility, to confirm whether funds are available, and to take other relevant steps necessary prior to commencing negotiations with the applicant.

3. Options

The Government will evaluate options for award purposes by adding the total cost for all options to the total cost for the basic requirement. Evaluation of options will not obligate the Government to exercise the options during grant performance.

4. Evaluation Panel

White paper submissions will be reviewed either solely by the responsible Research Topic Chief for the specific topic or by an evaluation panel chaired by the responsible Research Topic Chief. An evaluation panel will consist of technical experts who are Government employees or who are detailed under the Intergovernmental Personnel Act (IPA). Restrictive notices notwithstanding, one or more support contractors or advisors external to the US Government may be utilized as subject-matter-expert technical consultants. These individuals will sign a conflict of interest statement and a non-disclosure agreement prior to receiving proposal information.

Proposals will undergo a multi-stage evaluation procedure. The Research Topic Chief and other Government scientific experts will perform the evaluation of technical proposals first. Cost proposals will be evaluated by Government business professionals. Restrictive notices notwithstanding, one or more support contractors or advisors external to the US Government may be utilized as subject-matter-expert technical consultants. However, proposal selection and award decisions are solely the responsibility of Government personnel. Support contractor employees and advisors external to the US Government having access to technical and cost proposals submitted in response to this FOA will be required to sign a non-disclosure and a conflict of interest statement prior to receipt of any proposal submission. Findings of the evaluation panels will be forwarded to senior DoD officials who will make funding recommendations to the awarding officials.

Due to the nature of the MURI program, the evaluation panels and reviewing officials may on occasion recommend that less than an entire MURI proposal be selected for funding. This may be due to several causes, such as insufficient funds, research overlap among proposals received, or potential synergies among proposals under a research topic. In such cases, proposal adjustments will be agreed to by the Principal Investigator and the Government prior to final award.

5. General Information Regarding the Review and Selection Process

In accordance with Office of Management and Budget (OMB) guidance in parts 180 and 200 of Title 2, CFR, it is DoD policy that DoD Components must report and use integrity and performance information in the Federal Awardee Performance and Integrity Information System (FAPIIS), or any successor system designated by OMB, concerning grants, cooperative agreements, and TIA's as follows:

If the total Federal share will be greater than the simplified acquisition threshold on and Federal award under a notice of funding opportunity (see 2 CFR 200.88 Simplified Acquisition Threshold):

a. The Federal awarding agency, prior to making a Federal award with a total amount of Federal share greater than the simplified acquisition threshold, will review and consider any information about the applicant that is in the designated integrity and performance system accessible through SAM (currently FAPIIS)(see 41 U.S.C. 2313);

b. An applicant, at its option, may review information in the designated integrity and performance systems accessible through SAM and comment on any information about itself that a Federal awarding agency previously entered and is currently in the designated integrity and performance system accessible through SAM;

c. The Federal awarding agency will consider any comments by the applicant, in addition to the other information in the designated integrity and performance system, in making a judgment about the applicant's integrity, business ethics, and record of performance under Federal awards when completing the review of risk posed by applicants as described in 2 CFR 200.205 Federal awarding agency review of risk posed by applicants.

F. FEDERAL AWARD ADMINISTRATION INFORMATION

1. Unique Entity Identifier and System for Award Management (SAM)

System for Award Management (SAM): All Applicants submitting proposals or applications must:

a. Be registered in the SAM prior to submission;
b. Maintain an active SAM registration with current information at all times during which it has an active Federal award or an application under consideration by any agency; and
c. Provide its DUNS number in each application or proposal it submits to the agency.

SAM may be accessed at https://www.sam.gov

2. Federal Award Notices

Applicants whose proposals are recommended for award may be contacted by a Contract or Grant specialist to discuss additional information required for award. This may include representations and certifications, revised budgets or budget explanations, certificate of current cost or pricing data, subcontracting plan for small businesses, and/or other information as applicable to the proposed award.

The notification e-mail must not be regarded as an authorization to commit or expend funds. The Government is not obligated to provide any funding until a Government Contracting Officer or Grants Officer, as applicable, signs the award document.

The award document signed by the Contracting Officer or Grants Officer is the official and authorizing award instrument.

For **ARO**: ARO emails their awards/ modification documents to the awardees.

For **AFOSR**: AFOSR emails their awards/ modification documents to the awardees.

For **ONR**: ONR award/modification documents are only available via the Department of Defense (DoD) Electronic Document Access System (EDA) within the Wide Area WorkFlow e-Business Suite (https://wawf.eb.mil/). EDA is a Web-based system that provides secure online access, storage and retrieval of awards and modifications to DoD employees and vendors.

ONR creates an award notification profile for every award.

For grants, the notification profile will use the email addresses from the Application for

Federal Assistance, SF424, to notify the recipient of an award. ONR recommends that organizations provide a global business address for their entity in Field 5 (Application Information) of the SF424. ONR is using the following three email addresses entered by the grantee on the SF424 application to create the EDA notification profile:

i. Applicant Information (Field 5 - Email)
ii. Project Director / Principal Investigator (Field 14 - Email)
iii. Authorized Representative (Field 19 - Email)

For all other awards, the notification profile will use the email address from the Business Point of Contact to notify the recipient of an award.

***IMPORTANT*:** In some cases, EDA notifications are appearing in recipients' Junk Email folder. If you are experiencing issues receiving EDA notifications, please check your junk email. If found, please mark EDA notifications as "not junk."

If you do not currently have access to EDA, you may complete a self-registration request as a "Vendor" via https://wawf.eb.mil/ following the steps below:

1. Click "Accept"
2. Click "Register" (top right)
3. Click "Agree"
4. In the "What type of user are you?" drop down, select "Vendor"
5. Select the systems you would like to access (iRAPT at a minimum)
6. Complete the User Profile and follow the site instructions

Allow five business days for your registration to be processed. EDA will notify you by email when your account is approved.

To access awards after your registration has been approved, log into https://wawf.eb.mil/, select "EDA", select either EDA location, Select "Contracts", select your search preference, enter the Contract Number (or, if applicable, enter the Grant Number in the Contract Number field), and select "View".

Registration questions may be directed to the EDA help desk toll free at 866-618-5988, commercial at 801-605-7095, or via email at disa.ogden.esd.mbx.cscassig@mail.mil (Subject: EDA Assistance).

3. Reporting

If the Federal share of any Federal award may include more than $500,000 over the period of performance, the post award reporting requirements, Award Term and Condition for Recipient Integrity and Performance Matters (2 U.S.C. 200 Appendix XII), is applicable as follows:

a. Reporting of Matters Related to Recipient Integrity and Performance

(1) General Reporting Requirement. If the total value of your currently active grants,

cooperative agreements, and procurement contracts from all Federal awarding agencies exceeds $10,000,000 for any period of time during the period of performance of this Federal award, then you as the recipient during that period of time must maintain the currency of information reported to the System for Award Management (SAM) that is made available in the designated integrity and performance system (currently the Federal Awardee Performance and Integrity Information System (FAPIIS)) about civil, criminal, or administrative proceedings described in paragraph 2 of this award term and condition. This is a statutory requirement under section 872 of Public Law 110-417, as amended (41 U.S.C. 2313). As required by section 3010 of Public Law 111-212, all information posted in the designated integrity and performance system on or after April 15, 2011, except past performance reviews required for Federal procurement contracts, will be publicly available.

(2) Proceedings About Which You Must Report. Submit the information required about each proceeding that:

a. Is in connection with the award or performance of a grant, cooperative agreement, or procurement contract from the Federal Government;

b. Reached its final disposition during the most recent five-year period; and

c. Is one of the following:

(i) A criminal proceeding that resulted in a conviction, as defined in paragraph 5 of this award term and condition;

(ii) A civil proceeding that resulted in a finding of fault and liability and payment of a monetary fine, penalty, reimbursement, restitution, or damages of $5,000 or more;

(iii) An administrative proceeding, as defined in paragraph 5. of this award term and condition, that resulted in a finding of fault and liability and your payment of either a monetary fine or penalty of $5,000 or more or reimbursement, restitution, or damages in excess of $100,000; or

(iv) Any other criminal, civil, or administrative proceeding if:

(a) It could have led to an outcome described in paragraph 2.c.(i), (ii), or (b) of this award term and condition;

(c) It had a different disposition arrived at by consent or compromise with an acknowledgment of fault on your part; and

(d) The requirement in this award term and condition to disclose information about the proceeding does not conflict with applicable laws and regulations.

(3) Reporting Procedures. Enter in the SAM Entity Management area the information that SAM requires about each proceeding described in paragraph 2 of this award term and condition. You do not need to submit the information a second time under assistance

awards that you received if you already provided the information through SAM because you were required to do so under Federal procurement contracts that you were awarded.

(4) Reporting Frequency. During any period of time when you are subject to the requirement in paragraph 1 of this award term and condition, you must report proceedings information through SAM for the most recent five-year period, either to report new information about any proceeding(s) that you have not reported previously or affirm that there is no new information to report. Recipients that have Federal contract, grant, and cooperative agreement awards with a cumulative total value greater than $10,000,000 must disclose semiannually any information about the criminal, civil, and administrative proceedings.

(5) Definitions. For purposes of this award term and condition:

a. Administrative proceeding means a non-judicial process that is adjudicatory in nature in order to make a determination of fault or liability (e.g., Securities and Exchange Commission Administrative proceedings, Civilian Board of Contract Appeals proceedings, and Armed Services Board of Contract Appeals proceedings). This includes proceedings at the Federal and State level but only in connection with performance of a Federal contract or grant. It does not include audits, site visits, corrective plans, or inspection of deliverables.

b. Conviction, for purposes of this award term and condition, means a judgment or conviction of a criminal offense by any court of competent jurisdiction, whether entered upon a verdict or a plea, and includes a conviction entered upon a plea of nolo contendere.

c. Total value of currently active grants, cooperative agreements, and procurement contracts includes:

(i) Only the Federal share of the funding under any Federal award with a recipient cost share or match; and

(ii) The value of all expected funding increments under a Federal award and options, even if not yet exercised.

G. FEDERAL AWARDING AGENCY CONTACTS

One or more Research Topic Chiefs are identified for each SPECIFIC MURI TOPIC. Questions of a technical nature on a specific topic shall be directed to one of the Research Topic Chiefs identified in Section II. I entitled "SPECIFIC MURI TOPICS" of this FOA.

Questions of a policy nature for all three (3) services shall be directed to ONR as specified below:

ONR MURI Program Point of Contact:

Dr. Ellen Livingston
MURI Program Manager

Office of Naval Research
Email: ellen.s.livingston@navy.mil

Mailing address:
Office of Naval Research One Liberty Center
875 North Randolph Street, Suite 1020
Arlington, VA 22203-1995

Questions of a business nature for all three (3) agencies contact:

David Broadwell
Grants Officer,
Code 255 Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995
Email: david.broadwell@navy.mil

Questions submitted after the Q&A deadline, as noted in the table in Section II. D. 4 of this FOA, may not be answered.

FOA amendments, if any, will be posted on the Grants.gov webpage https://www.grants.gov/ under the agency's specific MURI announcement.

H. OTHER INFORMATION

1. Federal Funding Accountability and Transparency Act of 2006

The Federal Funding Accountability and Transparency Act of 2006 (Public Law 109-282), as amended by Section 6202 of Public Law 110-252, and expanded by the Digital Accountability and Transparency Act of 2014 (Public Law 113-101), requires that all agencies establish requirements for recipients reporting information on subawards and executive total compensation as codified in 2 CFR Part 170. Any company, non-profit agency or university that applies for financial assistance as either a prime or sub-recipient under this FOA must provide information in its proposal that describes the necessary processes and systems in place to comply with the reporting requirements identified in 2 CFR Part 170 Appendix A. Entities are required to meet reporting requirements unless an exception or exemption applies. Refer to 2 CFR Part 170, including Appendix A, for a detailed explanation of the requirements, exceptions, and exemptions.

2. Certification regarding Restrictions on Lobbying

Grant, Cooperative Agreement, and Technology Investment Agreement (TIA) awards greater than $100,000 require a certification of compliance with a national policy mandate concerning lobbying. Grant applicants shall provide this certification by electronic submission of SF424 (R&R) as a part of the electronic proposal submitted via Grants.gov (complete Block 17). The following certification applies likewise to each Cooperative Agreement and TIA seeking federal assistance funds exceeding $100,000:

a. No Federal appropriated funds have been paid or will be paid by or on behalf of the applicant, to any person for influencing or attempting to influence an officer or employee of an agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any Federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

b. If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the Federal contract, grant, loan, or cooperative agreement, the applicant shall complete and submit Standard Form-LLL, "Disclosure Form to Report Lobbying," in accordance with its instructions.

c. The applicant shall require that the language of this certification be included in the award documents for all subawards at all tiers (including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements) and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by Section 1352, title 31, U.S.C. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

3. Representation Regarding an Unpaid Delinquent Tax Liability or a Felony Conviction Under any Federal Law - DoD Appropriations

All grant applicants are **required to complete** the "Representation on Tax Delinquency and Felony Conviction" found at https://www.onr.navy.mil/Contracts-Grants/submit-proposal/grants-proposal.aspx by checking the "I agree" box in Field 17 and attaching the representation to Field 18 of the SF424 (R&R) as part of the electronic proposal submitted via Grants.gov. The representation reads as follows:

a. The applicant represents that it **____ is/ is not ____** a corporation that has any unpaid Federal tax liability that has been assessed, for which all judicial and administrative remedies have been exhausted or have lapsed, and that is not being paid in timely manner pursuant to an agreement with the authority responsible for collecting the tax liability.

b. The applicant represents that it **____ is/ is not ____** a corporation that was convicted of a felony criminal violation under any Federal law within the preceding 24 months. NOTE: If an applicant responds in the affirmative to either of the above representations, the applicant is ineligible to receive an award unless the agency suspension and debarment official (SDO) has considered suspension or debarment and determined that further action is not required to protect the Government's interests. The applicant therefore must provide information about its tax liability or conviction to the agency's SDO as soon as it can do so, to facilitate completion of the required consideration before award decisions are made.

4. Representation Regarding the Prohibition on Using Funds with Entities that Require Certain Internal Confidentiality Agreements

Agreement with the representation below will be affirmed by checking the "I agree" box in Field 17 of the SF424 (R&R) as part of the electronic proposal submitted via Grants.gov. The representation reads as follows:

By submission of its proposal or application, the applicant represents that it does not require any of its employees, contractors, or subrecipients seeking to report fraud, waste, or abuse to sign or comply with internal confidentiality agreements or statements prohibiting or otherwise restricting those employees, contractors, subrecipients from lawfully reporting that waste, fraud, or abuse to a designated investigative or law enforcement representative of a Federal department or agency authorized to receive such information.

Note that, as applicable, the bases for this representation are the prohibition(s) as follow:

a. Section 743 of the Financial Services and General Government Appropriation Act, 2015 (Division E of the Consolidated and Further Continuing Appropriations Act, 2015, Pub. L. 113-235)

b. Pub. L. 114-53, Continuing Appropriation Act, 2016, or any other Act that extends to fiscal year 2016 funds the same prohibitions as contained in section 743 of Division E, title VII of the Consolidated and Further Continuing Appropriations Act, 2015 (Pub. L. 113-235) and the Consolidated Appropriations Act, 2016 (Pub. L. 114-113).

c. Pub. L. 114-223, Continuing Appropriations Act, 2017, or any other Act that extends to fiscal year 2017 funds the same prohibitions as contained in section 743, Division E, title VII, of the Consolidated Appropriations Act, 2016 (Pub. L. 114-113) and the Consolidated Appropriations Act, 2017 (Pub. L. 115-31)

d. Pub. L. 115-56, Continuing Appropriations Act, 2018 and Supplemental Appropriations for Disaster Relief Requirements Act, 2017, or any other Act that extends to fiscal year 2018 funds the same prohibitions as contained in Section 743, Division E, title VII, of the Consolidated Appropriations Act, 2017 (Pub. L. 115-31) and the Consolidated Appropriations Act, 2018 (Pub. L. 115-141)

e. Pub. L. 115-245, Department of Defense and Labor, Health and Human Services, and Education Appropriations Act, 2019 and Continuing Appropriations Act, 2019, or any other Act that extends to fiscal year 2018 funds the same prohibitions as contained in Section 743, Division E, title VII, of the Consolidated Appropriations Act, 2018 (Pub. L. 115-41)

f. Any successor provision of law on making funds available through grants and cooperative agreements to entities with certain internal confidentiality agreements or statements.

5. Code of Conduct

Applicants for grants, cooperative agreements, or other transaction agreements as applicable are required to comply with 2 CFR 200.318(c), Codes of Conduct, to prevent real or apparent conflicts of interest in the award and administration of any contracts supported by federal funds. This provision will be incorporated into all assistance instruments awarded under this FOA.

6. Requirements Concerning Live Organisms

Use of Animals:

The DoD policies and requirements for the use of animals in DoD-supported research are described in DoD Instruction 3216.01, *Use of Animals in DoD Programs*, and SECNAVINST 3900.38C, *The Care and Use of Laboratory Animals in DOD Programs*. If animals are to be utilized in the research effort proposed, the Applicant must submit a Full Appendix or Abbreviated Appendix with supporting documentation (copies of Institutional Animal Care and Use Committee (IACUC) Approval, IACUC Approved Protocol, and most recent United States Department of Agriculture (USDA) Inspection Report) prior to award. For assistance with submission of animal research related documentation, contact the ONR Animal Use Administrator at (703) 696-4046. Guidance: https://www.onr.navy.mil/About-ONR/compliance-protections/Research-Protections/animal-use

Use of Human Subjects in Research:

a. Applicants must protect the rights and welfare of individuals who participate as human subjects in research awarded pursuant to this FOA and must comply with the requirements of the Common Rule at 32 CFR part 219 and applicable provisions of DoD Instruction 3216.02, *Protection of Human Subjects and Adherence to Ethical Standards in DoD-Supported Research* (2011), the DON implementation of the human research protection program contained in SECNAVINST 3900.39E (or its replacement), 10 USC 980 "Limitation on Use of Humans as Experimental Subjects," and when applicable, Food and Drug Administration (FDA) and other federal and state law and regulations.

b. For proposals containing activities that include or may include "research involving human subjects" as defined in DoDI 3216.02, prior to award, the Applicant must submit documentation of:

(i) Approval from an Institutional Review Board (IRB) (IRB-approved research protocol, IRB- approved informed consent document, and other material they considered); proof of completed human research training (e.g., training certificate or institutional verification of training for the principal investigator, co-investigators); and the Applicant's Department of Health and Human Services (DHHS)-issued Federal Wide Assurance (FWA), including notifications of any suspensions or terminations to the FWA),

(ii) Any claimed exemption under 32 CFR 219 101(b), including the category of exemption, supporting documentation considered by the Applicant's institution in making the determination (e.g., protocol, data collection tools, advertisements, etc.). The documentation shall include a short rationale supporting the exemption determination. This documentation should be signed by the IRB Chair or IRB vice Chair, designated IRB administrator or official of the human research protection program.

(iii) Any determinations that the proposal does not contain activities that constitute research involving human subjects, including supporting documentation considered by the Applicant's institution in making the determination. This documentation should be issued by the IRB Chair or IRB vice Chair, designated IRB administrator or official of the human research protection program.

c. Documentation must be submitted to the ONR Human Research Protection Official (HRPO), by way of the ONR Program Officer. If the research is determined by the IRB to be greater than minimal risk, the Applicant also must provide the name and contact information for the independent research monitor and a written summary of the monitors' duties, authorities, and responsibilities as approved by the IRB. For assistance with submission of human subject research related documentation, contact the ONR Human Research Protection Official (HRPO) at (703) 696-4046.

d. Research involving human subjects must not be commenced under any contract award or modification or any subcontract or grant subaward or modification until awardee receives notification from the Contracting or Grants Officer that the HRPO has approved the assurance as appropriate for the research under the award or modification and that the HRPO has reviewed the protocol and accepted the IRB approval or determination for compliance with Federal, DoD and DON research protection requirements. See, DFARS 252.235-7004. Guidance: http://www.onr.navy.mil/About-ONR/compliance-protections/Research-Protections/Human-Subject-Research.aspx

Biosafety and Biosecurity Requirements:

Applicants must comply with applicable provisions of DOD 6055.18-M, Safety Standards for Microbiological and Biomedical Laboratories, including ensuring compliance with standards meeting at least the minimum applicable requirements of the current edition of Centers for Disease Control and Prevention, "Biosafety in Microbiological and Biomedical Laboratories (BMBL)," and National Institutes of Health, "The NIH Guidelines for Research Involving Recombinant or Synthetic Nucleic Acid Molecules (NIH Guidelines)."

Research Involving Recombinant or Synthetic Nucleic Acid Molecules.

Applicants must not begin performance of research within the scope of "The NIH Guidelines for Research Involving Recombinant or Synthetic Nucleic Acid Molecules (NIH Guidelines)" until receiving notice from the Contracting or Grants Officer that ONR has reviewed and accepted the Applicant's documentation. In order for ONR to accomplish that review, an Applicant must provide the Contracting or Grants Officer, generally as part of an original proposal prior to award, sufficient documentation to enable the review, including:

a. A written statement that the Applicant is in compliance with NIH Guidelines. This statement should be made by an official of the institution other than the Principal Investigator and should be on university or company letterhead.

b. Evidence demonstrating that the proposed research protocol has been approved by an Institutional Biosafety Committee (IBC); and a copy of the Department of Health and Human Services (DHHS) Letter of Approval of the IBC, or the most recent letter from DHHS stating the IBC is in compliance with the NIH Guidelines.
Guidance: https://www.onr.navy.mil/About-ONR/compliance-protections/Research-Protections/Animal-Recombinant-DNA.aspx

7. Institutional Dual Use Research of Concern

As of September 24, 2015, all institutions and United States Government (USG) funding agencies subject to the United States Government Policy for Institutional Oversight of Life Sciences Dual Use Research of Concern must comply with all the requirements listed therein. If your research proposal directly involves certain biological agents or toxins, contact the cognizant Technical Point of Contact. U.S. Government Science, Safety, Security (S3) guidance may be found at https://www.phe.gov/s3/dualuse.

8. Department of Defense High Performance Computing Program

The DoD High Performance Computing Program (HPCMP) furnishes the DoD S&T and RDT&E communities with use-access to very powerful high performance computing systems. Awardees of ONR contracts, grants, and other assistance instruments may be eligible to use HPCMP assets in support of their funded activities if ONR Program Officer approval is obtained and if security/screening requirements are favorably completed. Additional information and an application may be found at https://www.hpcmo.hpc.mil/.

9. Project Meetings and Reviews

Individual program reviews between the DoD awarding agency and the performer may be held as necessary. Program status reviews may also be held to provide a forum for reviews of the latest results from experiments and any other incremental progress towards the major demonstrations. These meetings will typically be held at the Applicant's research facility. Interim meetings are likely, but these will be accomplished via video telephone conferences, telephone conferences, or via web-based collaboration tools.

I. SPECIFIC MURI TOPICS

ONR:

Topic 1: Stimuli-Responsive Materials based on Triggered Polymer Depolymerization

Topic 2: Quantum Benefits without Quantum Fragility: The Classical Entanglement of Light

Topic 3: Mathematical Methods for Deep Learning

Topic 4: Spin and Orbital Angular Momentum (SAM & OAM)

Topic 5: Photonic High-Order Topological Insulators (PHOTIs)

Topic 6: Active Topological Mechanical Metamaterials

Topic 7: Harvesting Oxygen from the Ocean

Topic 8: Exploring Oxidation and Surface Phenomena of Multi-Principal Element Alloys

Topic 9: The Physics of High-Speed Multiphase-flow / Material Interactions

Topic 10: Combining Disparate Environmental Data Into a Common Framework

ARO:

Topic 11: Adaptive and Adversarial Machine Learning

Topic 12: Axion Electrodynamics beyond Maxwell's Equations

Topic 13: Engineering Endosymbionts to Produce Novel Functional Materials

Topic 14: Information Exchange Network Dynamics

Topic 15: Mathematical Intelligence: Machines with More Fundamental Capabilities

Topic 16: Quantum State Engineering for Enhanced Metrology

Topic 17: Solution Electrochemistry without Electrodes

Topic 18: Stimuli-Responsive Mechanical Metamaterials

AFOSR:

Topic 19: Machine Learning and Physics-Based Modeling and Simulation

Topic 20: Fundamental Design Principles for Engineering Orthogonal Liquid-Liquid Phase Separations in Living Cells

Topic 21: Modeling, Prediction, and Mitigation of Rare and Extreme Events in Complex

Topic 1: (ONR) Stimuli-Responsive Materials based on Triggered Polymer Depolymerization

Background: Stimuli-responsive materials are those that respond to their environments in response to defined internal or external events to perform a dynamic function. Stimuli could be optical, thermal, presence of selective chemicals/enzymes/microbes, stress or strain, presence of electric or magnetic fields, and so forth. When that stimulus results in the controlled partial or full depolymerization of a polymer, it has the potential to enable a variety of applications ranging from crack mitigation in structural polymers; coatings that are easily removed without damaging the substrate; facile repair and recycling of composites; novel biomaterials for drug delivery and tissue scaffolding; reprocessing, repair or degradation of electronics; and as novel substrates in nano-fabrication and additive manufacturing.

Polymerization reactions are reversible. While most common polymer reactions are exothermic and lead to stable polymers with high polymerization ceiling temperatures, low ceiling temperature polymers favor the reverse (depolymerization) reaction at room temperature and are inherently unstable. Only a few examples of this phenomenon have been known for some time. Recent work has moved towards novel methods to cap these polymer chains to block depolymerizaton and to provide both useful stability and a facile trigger to initiate depolymerization. Such triggered depolymerization materials are finding practical applications in drug release and lithography. However, these are high cost point, low volume applications that really don't require much in the way of mechanical/thermal/chemical properties. Traditional polymer applications require high chemical and thermal stability, strong mechanical properties, and facile processing at a low cost point. Traditional polymers typically have favorable reaction thermodynamics and high polymerization ceiling temperatures that help deliver these favorable properties. Can low ceiling temperature, less thermodynamically favored polymers be made that have these desirable properties? Are the chain end caps that trap the unstable polymers in a metastable state robust enough to allow full utilization of these novel polymer backbones? If the answer to these questions is positive, then a new and largely unexplored chemical space will be opened up for new polymer backbone chemistries. What triggers can be used that are self-enabled when needed (stress initiated depolymerization, relaxed molecules repolymerize) or are orthogonal to stressors observed during the useful lifetime (UV, moisture, chemical stability, typical mechanical and thermal peak loads), and, can they be applied when desired by facile means? Finally, are there other approaches to enabling stimuli-responsive depolymerization beyond stabilizing low ceiling temperature polymers?

Objective: The objectives of this MURI are: (1) to understand the underpinning interplay between kinetics and thermodynamics, including enthalpy/entropy compensation, needed to develop materials with specific polymerization ceiling temperatures; (2) to be able to predict, a priori, the thermal, mechanical, and chemical stability of these metastable materials; (3) to develop an improved understanding of endcapping and other stabilization mechanisms that would allow full use of these materials above their polymerization ceilings and; (4) to use this new knowledge to develop novel triggers that don't compromise performance and allow facile depolymerization on demand. Alternative approaches to facile depolymerization may also be investigated. The long-term goal is to attain polymers with inherently strong properties and controlled depolymerization to enable applications relevant to DoD needs.

Research Concentration Areas: Suggested multidisciplinary research areas include, but are not limited to: (1) balanced investigation of computational, synthetic, and characterization approaches towards new polymers that are predicted to have both on-demand depolymerization characteristics as well as useful chemical stability, mechanical and thermal properties; (2) theoretical and experimental studies of triggers and transition phenomena in response to stimuli; (3) studies of reaction mechanisms and kinetics; and (4) machine learning, high throughput computational and experimental tools to enable researchers to predict, create, and mature new classes of polymeric materials.

Anticipated Resources: It is anticipated that awards under this topic will be no more than an average of $1.5M per year for 5 years, supporting no more than 6 funded faculty researchers. Exceptions warranted by specific proposal approaches should be discussed with the topic chief during the white paper phase of the solicitation.

Research Topic Chiefs:
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Topic 2: (ONR) Quantum Benefits without Quantum Fragility: The Classical Entanglement of Light

Background: Although "entanglement" is often considered to be a quantum effect, the classical entanglement of light is inspiring a deeper look at the fundamental quantum-classical boundary, while showing considerable promise in a broad range of applications.[1,2] Classically entangled beams have been shown to violate Bell's inequality[3,4] and manifest a degree of non-locality[5], which have long been assumed to be exclusive characteristics of the quantum domain. Yet, in contrast, quantum-entangled beams are difficult to generate at high intensity and are susceptible to environmental degradation, while classically entangled beams can have arbitrarily high intensity and are environmentally robust. Therefore, the promise of classical entanglement to yield quantum-like advances unencumbered by the confines of single-photonics, motivates this MURI topic, which summons researchers in multiple disciplines, including quantum optics, classical optics, pure and applied mathematics, imaging, and information science.

Analogous to quantum entanglement, classical entanglement requires inseparability in which the mathematical description of an optical beam cannot be expressed as a simple product involving independent degrees-of-freedom, such as intensity, temporal profile, or polarization. Instead, each entangled variable is interdependent in a known way, enabling it to serve as an ancilla, or measurement aid, supplying prior information for every other entangled variable, where each variable carries unique information. For N repeated measurements, entanglement promises to revolutionize metrology through Heisenberg-limited uncertainty that scales remarkably as 1/N in contrast to the $1/\sqrt{N}$ shot-noise scaling. Quantum measurements cannot reach the Heisenberg limit due to the inevitable presence of dissipation[6-8], but classically entangled measurements are already approaching this limit.[9-11] A classical analog to quantum squeezing has also been demonstrated, enabling measurement uncertainty to be redistributed from a key information-carrying degree-of-freedom to a less relevant one.[4] The measurement of high-speed trajectories of arbitrary profile objects has also been demonstrated, first with entangled orbital angular momentum states[10] and more recently with maximally entangled random fields[11]. Polarization entangled beams have yielded smaller focal spots than conventional beams, which could benefit vital optical lithographic and storage/readout technologies as well as fundamental studies of light-matter interaction. The creation of non-diffracting pulsed optical beams has also been demonstrated in which strong space-time correlations, derived from classical entanglement, mitigate the spread of the time-averaged beam.[12] Classical entanglement has inspired alternative perspectives in image processing[5], communication[13,14], and computation[15,16]. Interestingly, classical entanglement appears to resolve a fundamental issue in optics by completing the subset of real 4×4 matrices corresponding to physically meaningful Mueller matrices[17], which prompts a re-examination of the mathematical framework of beam description. The classically entangled subset of Mueller matrices, while largely unexplored, may be ubiquitous in that entangled light may actually be the most common state.

Objective: The objective of this MURI is to explore the quantum-like properties of classical light to advance our fundamental understanding of electromagnetic radiation, while seeking advances in metrology, imaging, and information science. A multidisciplinary research effort will bring together experts in quantum optics, classical optics, pure and applied mathematics, and information and image science to reformulate key principles of optics in light of classical entanglement, explore theoretical methods to describe and exploit classically entangled optical phenomena, and develop the necessary experimental tools to study and control these novel optical beams.

Research Concentration Areas: Suggested research areas include but are not limited to: (1) Exploring the physics and mathematics of the quantum/classical boundary to develop a full quantum theory to describe classically entangled beams; (2) Develop the mathematical framework and the physical and information theory behind the flow of entropy (and thereby loss of information) between the degrees of freedom of optical beams in which multiple degrees of freedom are entangled; (3) Experimental studies demonstrating novel measurements techniques utilizing classically entangled beams to improve on the classical precision limit in metrology; (4) Exploration of novel applications using unique beam properties, imaging, and/or information transport/processing schemes.

Anticipated Resources: The award under this topic is expected to be approximately $1.5M per year for 5 years, which should support full engagement of 5-6 research groups.

Research Topic Chiefs:
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Topic 3: (ONR) Mathematical Methods for Deep Learning

Background: Deep learning (DL) has emerged as a powerful approach for knowledge acquisition, and analysis and exploitation of large datasets. In particular, it has made substantial advances in visual object classification and speech recognition. Innovative DL architectures for specific applications in artificial intelligence and autonomy continue to be developed at a fast pace. DL is also making inroads into other disciplines such as the physical and biological sciences for developing better predictive models and potential discovery of important phenomena from the data. However, mathematical tools for understanding the many successes of DL do not yet exist. For example, it is not clear what classes of concepts can be learned by a deep network; there is no principled way of designing the DL architecture; and why stochastic gradient descent (SGD), a seemingly simple optimization strategy, is so effective in finding the global or a good local minimum of the high-dimensional, non-convex cost function. More importantly, DL is also a major technology intended for decision-making in safety critical applications. However, since the current approach to verification of DL is based on purely empirical test and evaluation using annotated datasets, it becomes impractical to obtain a reliable performance envelope. Moreover, empirical verification is impossible for a deployed agent that encounters conditions it was not trained for, or for an unsupervised self-learning agent because the data is not annotated and it is not even clear what to test the agent on. Therefore, mathematical tools are needed for analyzing what the agent has learned and what the confidence level is, for controlling and improving its learning, and for predicting its performance under various conditions. Such tools, will play an essential role in developing analytical and formal methods for verification and validation of the agent, and will lead to advances for better explanations of its decisions and building trust in its behavior. DL is a challenging complex nonlinear system. However, certain promising early advances in the mathematics of DL such as connections between PDEs and DL, methods for growing DL architectures, and formulating beneficial cost functions, indicate that principled, sound, and systematic methods for the design and analysis of DL could be achieved.

Objective: Develop mathematical, formal, and optimization methods for designing Deep Learning architectures, training them, analyzing their performance, and predicting their behavior under different conditions with provable guarantees. These methods should be applicable to various models including neural networks, compositional networks, and-or graphs, and similar feedforward and recurrent learning and inference architectures.

Research Concentration Areas: We are particularly interested in learning models of complex visual activities for 4D scene understanding. Expertise in mathematics of nonlinear systems, formal methods, statistics, large-scale optimization and other disciplines are needed to develop theory and algorithms for the design and analysis of deep learning agents. This topic requires investigating a number of challenging basic questions that would lead to: (a) Principled methods for finding the class of architectures that are best suited for learning given concepts, and are capable of generalization to new concepts and transfer learning; (b) Methods for formulating the cost function to prevent the agent from learning behaviors detrimental to the user's goals; (c) Training algorithms that go beyond SGD to make learning faster and more effective; (d) Methods that organize the data to improve learning in terms of quality and speed, and do so automatically; (e) Methods that map DL architectures to logical or causal structures suited for deeper inference and better explanations; (f) Methods for combining formal methods with machine learning to analyze DL behavior; (g) Effective methods for statistical testing of DL approaches; and (h) Methods for characterization and reliable estimation of uncertainty in the agent's inference.

Anticipated Resources: It is anticipated that awards under this topic will be no more than an average of $1.5M per year for 5 years, supporting no more than 8 funded faculty researchers. Exceptions warranted by specific proposal approaches should be discussed with the topic chiefs during the white paper phase of the solicitation.

Research Topic Chiefs:

Dr. Behzad Kamgar-Parsi, ONR 311, (703) 696-5754, behzad.kamgarparsi@navy.mil
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Topic 4: (ONR) Spin and Orbital Angular Momentum (SAM & OAM)

Background: The physical representation of Orbital Angular Momentum (OAM) of light is dependent on its field spatial distribution[1], which is independent from its polarization or spin. Spin angular momentum (SAM) of light is often associated with circular polarization in which every polarization vector rotates. Each photon with circular polarization carries with it a basic unit of

SAM = ±h/2π, with the sign of the SAM depending on whether it is left- or right circularly polarized. The unique potential of OAM and SAM derives from the underlying nature of internal OAM, wherein the origin-independent angular momentum of a photon can be associated with a helical or twisted wave-front and wherein that wave-front is defined as the set of points within the field having identical phase. The nature of this peculiar OAM wave-front causes photons to interact (or rather avoid interaction) with matter in ways that are largely unexplored. OAM wave-fronts possessing higher Bessel Gauss orders have been shown to exhibit self-healing properties and are being explored for application in communications, sensing, and for improved laser propagation[2]. While controlling polarization can alone provide useful information about the structure of crystalline surfaces, wave-fronts carrying OAM and SAM may provide additional information, by permitting entirely new sensing and material interactions between photons and atomic structures. These unique OAM & SAM characteristics may ultimately permit enhanced propagation within highly scattering and/or refracting environments and optical elements. Quantum mechanical transition laws are based principally on conventional optical sources (no OAM). By incorporating OAM into these laws, formally forbidden transitions now become available for exploitation. This feature alone provides an entirely new perspective for spectroscopy and other related areas.

This interaction between photons having OAM and SAM at the atomic level opens potentially new avenues of matter interaction, where periodic excitation with materials may result in localized maxima or minima that enables new sensing, transmission or increased conversion efficiency. In the field of nonlinear dynamics, spiral wave phenomena in excitable media have long been of interest [3–6]. In these cases, the spiral waves are in the states of coupled phase oscillators. For example, the periodic function interaction with atmospheric or water column turbulence may result in a maxima condition for transmission based on reduced turbulent induced refraction, or atmospheric scatter and possibly atmospheric absorption[7]. The interaction of the photon with Mie or Rayleigh resonances produce electromagnetic field localizations and enhancements, and those with OAM and SAM which change both the magnitude of the interaction, and the directionality, are of interest. Of particular interest is the recent realization of fast responding, fractional non-linear optical OAM and SAM phase modulators and metamaterials. These devices offer the potential to reduce turbulence induced refraction when the atmospheric propagation path indicates (e.g. estimated by Fried's coherence length (r0), Greenwood Frequency (fG), Isoplanatic Angle, Rytov Number, etc.) that beam bifurcation or break-up[8] would normally occur. This MURI primarily seeks to understand the fundamental underlying physics and potential implications of novel photonic OAM and SAM interactions with matter in its various phases (solid, liquid and gas). Material interactions with bulk periodic or aperiodic oscillations, but having a structured morphology, may see significant increases in photon transmission or interaction arising from the unique photonic-EM interactions at the atomic or molecular level[9]. At higher photon densities, the resulting interaction and resonances with matter may even induce Plasmon creation well below expected bulk thresholds, relevant to several practical electronic device applications. Furthermore, investigation of photonic OAM and SAM with newly realized optical “metamaterials” materials may yield devices with highly variable volumetric responsivities. The potential for modifying the scattering properties of light using such structures would result in novel optical capabilities including a tunable (positive to negative) refractive index devices. Such devices could, if realized, be designed to respond uniquely to a particular OAM phase or "spin". A current analog to this can be found in two-dimensional polarized surfaces which can be structured to exhibit high transmissivity and/or high impedance to particular incident EM wavefronts[10]. As with traditional polarizers, both coherent and incoherent photonic OAM and SAM devices can be used to explore novel beam combining concepts. Similar and related benefits have been shown when using "Twisted X-Rays", which also exhibit OAM, with periodic X-ray diffraction methods in determining the atomic scale structure of matter[11].

Objectives: The objective is to leverage the current understanding of light-matter properties, and extend the understanding of photon-spin-matter interactions, beyond simple bulk photon or polarization angles currently used. OAM and SAM offer a potential advantage by creating localized maxima or minima based on the structure and periodicity of material that a photon interacts with, even under exposure in high electromagnetic fields and/or at high laser powers. For example, the resulting advantages from localized field enhancements in the electromagnetic material response could result in significantly improved conversion efficiency, reduced transmission losses, or higher signal coherence. The primary outcome of this interdisciplinary research is to explore and document a new branch of material-light interactions that fundamentally changes our basic understanding of electromagnetic responses in turbulent atmospheric transmission and interaction with materials in general.

Research Concentration Areas: (1) To perform experiments that generate and characterize linear and even non-linear responses from OAM and SAM in various phases of materials, including the atmosphere, addressing questions related to the photon creation physics and control, as well as the scattering and absorption properties. (2) To devise and study methods of integrating photonic OAM and SAM responses into metamaterials, including the resulting synergistic properties, and the challenges of generating OAM and SAM in photons and the resultant responses in turbulent or multilayer optical dielectric structures. (3) To develop robust predictive simulations of the interaction of photons as electromagnetic waves with OAM and SAM characteristics, by merging modern wave-optical computational electromagnetic codes with particle and/or continuum models for material response behaviors.

Anticipated Resources: Anticipated award(s) made under this topic are expected to be no more than $1.5M per year for 5 years (on average), and supporting no more than five (5) funded faculty researchers, and no less than twelve (12) doctoral students. Exceptions warranted by specific proposal approaches should be discussed with the topic chiefs during the white paper phase of the solicitation.

Research Topic Chief:

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Topic 5: (ONR) Photonic High-Order Topological Insulators (PHOTIs)

Background: The discovery of topological phases of matter has led to a paradigm shift in control of states and modal dispersions within engineered materials. Topological insulators (TIs) enable the generation of electronic, photonic, and acoustic modes exhibiting both spatial and temporal robustness, known as topological protection. Most notably, TIs can facilitate wave propagation that is entirely resilient to disorder, irrespective of manufacturing precision or unpredictable defects induced by the operational environment. Current TIs are seriously limited by the dimensionality of the protected states that are necessarily *one* dimension lower than the host TI material. This has limited the development of new applications as well as fundamental scientific advances with TIs. In particular, incorporating the robust features of TIs in engineering applications has not yet been achieved. Moreover, there are only a couple hundred known TIs to date.

The recent discovery of higher-order topological insulators (HOTIs) provides the potential to overcome the limitations on the dimensionality of topological protection. HOTIs exhibit protected states that are themselves lower-order TIs, and can therefore enable topological protection over an extended range of dimensionalities. This topic seeks to answer the question, “Can topological protection be provided to photonic and electronic states in all dimensions lower than that of the host system?” Thus it addresses one of the key scientific challenges in utilizing TIs for practical applications - namely that the dimensionality of the protected states is necessarily one dimension lower than that of the host TI material. The introduction of HOTIs will enable ensembles of TIs which will give rise to the high-order TI behavior, i.e., provide topological protection for states with dimensions N-1, N-2, …, where N is the dimension of the HOTI host system. This is will require overcoming both theoretical and synthetic challenges for designing and fabricating these new material architectures.

Current findings indicate that 3D HOTIs can now be designed to protect 2D, 1D, and 0D states. Experiments on 2D HOTIs exploiting microwaves, photonics, and acoustics have demonstrated the topological protection of 0D states, but a multi-investigator program is needed to strengthen the connection between theory and experiment. The ability of HOTIs to bring robustness to states of all dimensionalities is an attractive opportunity for materials and metamaterials, especially at the micro- and nano-scale where maintaining manufacturing precision is both challenging and costly. It is, however, clear that much of the material space for creating these envisioned HOTI architectures remains unexplored. Further, scientific understanding for designing HOTI –based material architectures within certain application domains does not exist. Equally poor is understanding of limits on implementing HOTI concepts in various material domains and the fundamental stability (chemical or mechanical) of new HOTI materials. Photonic HOTIs

(PHOTIs) appear to be particularly suitable for exploring associated fundamental concepts such as reprogrammable functions through dynamic changes to HOTI architecture, protection against temporal fluctuations, and inter-coupling of 0D, 1D and 2D HOTI- protected modes.

The complexity of these new materials systems will require a close multidisciplinary interaction between computational science, physics, optics, chemical synthesis and nanofabrication. The enabling science is expected to provide a powerful new capability for designing and fabricating HOTI architectures across different material and functional domains.

Objective: Establish a scientific basis for designing and demonstrating higher-order topological insulator material architectures.

Research Concentration Areas: Areas of interest include but are not limited to: (1) New PHOTI material or metamaterial architectures that can be theoretically conceived, enabling combinations of multidimensional protected modes within 2D and 3D systems; (2) Key applications/devices that can be enabled by metamaterial PHOTIs; (3) Materials engineering to create 2D HOTI phases in 3D materials.

Anticipated Resources: It is anticipated that awards under this topic will be no more than an average of $1.5M per year for 5 years, supporting no more than six funded faculty researchers. Exception warranted by specific proposal approaches should be discussed with the topic chiefs during the white paper phase of the solicitation.

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Topic 6: (ONR) Active Topological Mechanical Metamaterials

Background: Research in the area of metamaterials has been rapidly evolving, offering today a versatile platform to realize materials with electromagnetic, acoustic, and mechanical properties that go well beyond what is naturally obtainable. One prominent example in the field of mechanics is metamaterials that permit topologically protected sound waves capable of propagating around obstacles without backscattering and insensitive to materials imperfections. While much of the work on topological metamaterials has been focused on tailoring waves, there has been recent work in the area of mechanical metamaterials with an emphasis on static phenomena involving folding mechanisms, large deformations, and stress focusing. One aspect is the possibility of designing the topology of the band diagram at low frequencies to induce unique phenomena in their static response.

An intriguing opportunity is breaking time-reversal symmetry in static mechanical systems by combining large nonlinearities with suitable topological features. The concept of non-reciprocal elastic systems can be extended to active topological metamaterials, in which moving fluids may bias the metamaterial and imprint topological protection to its mechanical response. New theoretical approaches are needed to understand the coupled active fluid-elastic effects and microfluidic hydrodynamic interactions with the lattice. Another interesting possibility is the creation of soft topological mechanical metamaterials using microscopic building blocks subject to thermal fluctuations such as polymers or colloids. Inspired by advances in the field of condensed matter physics, topological mechanical metamaterials hold the promise to change the way we design the interaction of materials with static forces and the propagation of elastic waves. Significant work is required to understand and model these materials, and bring these proof-of-concept realizations to viable applications of broad interest in mechanics.

Objective: The objective of this MURI is to explore a new class of topological mechanical metamaterials with active constituents enabling dynamically reconfigurable, topologically robust structures. A multidisciplinary research effort will bring together physics, engineering, materials science, and mathematics, in order to design and synthesize new topological metamaterials with tailored elastic responses to realize synthetic material platforms for statics and mechanics.

Research Concentration Areas: Suggested research areas include but are not limited to: (1) Exploring the physics and mathematics resulting from topological mechanical metamaterials that break reciprocity and macroscopic reversibility; (2) Development of new approaches to design and characterize mechanical metamaterials, with particular emphasis on active and non-reciprocal behavior; (3) Development of scalable fabrication techniques to implement such material in a reconfigurable environment using the opportunities offered by additive manufacturing; (4) Studies of self-assembled topological metamaterials using soft matter systems that are characterized by diffusion, strong thermal fluctuations, and many body interactions; (5) Demonstration of active mechanical metamaterials with tunable properties; (6) Exploration of novel applications of mechanical metamaterials such as topologically protected acoustic devices and new soft robotic mechanisms.

Anticipated Resources: It is anticipated that awards under this topic will be no more than an average of $1.5M per year for 5 years, supporting no more than six funded faculty researchers. Exception warranted by specific proposal approaches should be discussed with the topic chiefs during the white paper phase of the solicitation.

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Topic 7 (ONR): Harvesting Oxygen from the Ocean

Background: The creation of an efficient artificial gill to extract dissolved oxygen from the ocean has not yet been achieved. Oxygen is also available in the ocean in the form of oxygen bound to hydrogen and new catalysis capabilities may provide the possibility of extracting such bound oxygen. Oxygen is a valuable commodity for undersea Navy/Marine operations for life support, as well as an alternative fuel supply for submersible drones. This MURI focuses on the fundamental scientific advances needed to synchronize the extraction, transport and storage of oxygen at a production rate sufficient for these purposes, even in regions of low dissolved oxygen. Recent research identified catalysts that are capable of extracting bound oxygen from natural water sources including ocean water. (*Energy Environ. Sci.,* 2011, 4, 499-504). Simultaneously, the field of porous materials has been advancing rapidly with the discovery of many new materials with highly tunable properties, including porous liquids that could enable highly coordinated storage coupled with transport. High throughput screening and computational modeling will greatly enhance identifying efficient catalysts as well as predicting the feasibility and value added of coupling reactions. This MURI seeks to establish a scientific foundation building on research advances across fields in chemistry, materials science and computational modeling that will generate new scientific principles to optimize the efficiency and coordination of extraction, transport and storage of oxygen from the ocean.

Objectives: The objective of this program is for a multidisciplinary team to discover integrated approaches to oxygen extraction, transport and storage. Two scientific challenges are key to this project: (1) Developing the optimum catalyst for electrolysis of water such that the inherent interference of salts and organics is obviated. (2) Exploring the thermodynamic and kinetic properties of oxygen binding and release to drive the generation and release process. Meeting these objectives could be done using synergistic state-of-the-art design/synthesis/testing protocols. It is expected that bound oxygen to hydrogen in water (as opposed to dissolved O_2) be the source of molecular oxygen, but any approach to split water is acceptable. The MURI team should consider the possibilities of finding materials that could serve as water purification membranes such that extant electrolysis methods could be employed or find a completely new class of catalyst. This should be done using state-of-the-art design/synthesis/testing concepts that effectively choreograph the activities of: (i) computational exploration of chemical space using high throughput quantum-based quantum methods with machine learning and other informatics-based tools, (ii) materials synthesis and (iii) materials testing, all in a closed loop manner such that the tests can synergistically inform the computational search to converge on an optimal solution. Any power source needed for the electrolysis should be considered including use of batteries or other energy storage devices as well as in-situ power generation from mechanical motion, theromoelectrics, etc. Oxygen storage is another program objective and could be accomplished (i) in the form of a chemical compound that could be quickly reversed to allocate the O_2 when needed, or (ii) in the form of entrapment in porous materials like porous liquids, or porous solids including Metal-Organic Frameworks (MOFs) and related materials such as Covalent Organic Frameworks (COFs), and Zeolitic Imidazolate Frameworks (ZIFs). Because this component of the project depends on the oxygen generation methods described above, a strong connection with the computational and synthetic teams is required. Any other O_2 store-and-release methods are also acceptable. The final objective of this project should focus on gas transfer, either by passive diffusion or using facilitated oxygen transport in bioinspired membranes among other options. As above, we require that the design of gas transport methods be intimately linked with the search for materials, synthesis and analysis components of this project.

Research Concentration: A balanced scientific team including appropriate expertise for this problem in: (1) chemistry; (2) materials science; (3) bioscience; and (4) computational modeling.

Anticipated Resources: Awards under this topic will not exceed an average of $1.5M /year for 5 years, supporting ~6 faculty researchers. Exceptions warranted by specific proposed approaches should be discussed with the topic chief during the white paper phase of the solicitation.

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Topic 8: (ONR) Exploring Oxidation and Surface Phenomena of Multi-Principal Element Alloys

Background: Multi-principal element alloys (MPEAs) [also referred to as high entropy alloys (HEAs) and compositionally-complex alloys (CCAs)] are based generally on five or more principal elements in similar amounts, that provide a promising new approach to alloy discovery leading to a vast new compositional space with millions of unexplored alloy possibilities. In particular, the alloys of light-element MPEAs (LMPEAs) and the refractory MPEAs (RMPEAs) are of interest. The LMPEAs contain Mg, Li, Al, Si, Ca, Sc, Zn, Mn, Cu, Fe, Sn, Ti, etc.; and form alloys with densities lower than that of conventional Ti alloys, but with comparable strength. The RMPEAs contain elements such as Nb, Mo, Hf, Ti, V, Zr, W, and Ta; and form temperature-stable high- strength alloys.

MPEAs have generated considerable interest in the structural materials community; some MPEAs have exhibited superior strength, durability, and physical properties that are unobtainable from traditional alloys. However, to date MPEAs have been limited by their corrosion behavior. One major factor controlling oxidation and/or corrosion of traditional alloys are the properties of the oxide films that form on the exposed surfaces. Passive (corrosion-resistant) alloys tend to spontaneously form stable, protective films upon environmental exposure. The compositional complexity that makes MPEAs interesting from a mechanical standpoint also makes their oxidation / corrosion behavior much more complex than conventional alloys. Light elements like

Mg in LMPEAs are electrochemically active and form porous unprotective oxides. In the RMPEAs, many of the most common refractory-metal (Mo, V, W, etc.) oxides can volatilize at high temperatures, which can lead to film rupture and breakdown.

Another complexity results from the second-phase particles and precipitates that strengthen many MPEAs. Electrochemistry differences between the matrix and these particles lead to local galvanic effects that can disrupt the passive film chemistry and cause local stress states, leading to film decohesion and alloy pitting. The fundamental thermochemistry of MPEAs need to be understood, and the thermokinetic parameters must be carefully characterized to enable the prediction of preferred surface chemistry.

Stimulating robust MPEA passivation on a single disordered solid solution, a solid solution with ordered precipitates, or several ordered and disordered phases, requires detailed knowledge of aspects of electrochemistry and the chemical kinetics of oxidation which are is influenced strongly by processing variables, environment, chemical composition, phase transformations, microstructure, and compositional transport. Elemental additions, such as Al, Cr, or Si, form protective oxides over a wide temperature range on conventional alloys. However, in more complex MPEA's, Al, Cr, or Si may be negatively influenced by divergent migration/diffusion rates with other MPEA elements, partitioning tendencies, and clustering affinities. This presents many fundamental questions regarding element/alloy oxidation kinetics. What are the effects of major and minor elemental additions, local stress variations from diverse coefficients of thermal expansion, varying atomic sizes, variable oxide growth kinetics on the microstructure and passive films in MPEAs?

Objective: The objective of this project is to create the fundamental understanding of the surface reactions and interactions of the MPEAs that lead to the formation of protective oxides. The research will establish a detailed knowledge-base on the preferential oxide formation on MPEA surfaces, and the role of various elements in facilitating/opposing passivation, the function of mechanics in promoting oxide-substrate cohesion, the influence of phase stability of the oxide and the underlying microstructure, the influence of heterogeneities on the alloy surface in the oxide, and elemental diffusion and transport rates among MPEA phases. This foundational knowledge, with the concomitant models and simulations, will introduce a new pathway to rapidly design and create MPEAs that are resistant to extreme environments.

Research Concentration Areas: The goal of the research is to predict and understand the thermodynamics, kinetics, and mechanics of oxidation mechanism(s) for MPEAs, preferably RMPEAs and LMPEAs. This program requires an integrated multi-disciplinary approach that may include experimental surface science, materials science and mechanical metallurgy, computational thermodynamic phase stability and phase transformation modeling, corrosion science and oxidation, electrochemistry, and data science that addresses the complexity issues and emergent behaviors in these systems. Research topics include, but are not limited to: 1) mapping of the macroscopic thermo-chemical properties of the materials in the large-dimensional composition space using a combination of high-throughput computational approaches (such as CALPHAD), targeted quantum-simulations, and high-throughput experimental validation; 2) atomistic simulations to determine the surface energetics, elemental segregation due to oxidation, and prediction of kinetics parameters (such as relevant diffusion coefficients); 3) characterization of phase equilibria and non-equilibrium solidification as a function of temperature and its relation to corrosion properties; 4) high-throughput oxidation experiments; 5) rapid multi-scale characterization tools to determine oxide/substrate interactions under environmental stimuli, and oxide film composition, including spacial variations of chemistry and mechanical stress modes and values at relevant length scales; 6) informatics (machine learning/data science) tools that enable a data-intensive exploration of oxide film properties as a function of alloy composition, mechanical and environmental variables, diffusion, and related parameters; and 7) materials synthesis and characterization including the role of processing contributing to variable microstructures and compositional evolution.

Anticipated Resources: It is anticipated that awards under this topic will be no more than $1.5M per year for five years, supporting 5-6 faculty researchers.

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Topic 9: (ONR) The Physics of High-Speed Multiphase-flow / Material Interactions

Background: High-speed multiphase-flow / material interactions have first-order effects on numerous applications such as flight through rain or dust; planetary entry flows in dusty atmospheres; heat-shield spallation; liquid-film cooling; explosive dissemination, and atmospheric dispersal of liquid agent released at high-speed; and liquid-fuel injection, breakup, evaporation, and mixing in scramjets. Subsonic multiphase-flows, including the interaction with solid surfaces, have been extensively studied. Progress in the understanding and prediction of such flows has been achieved by performing coordinated computational and experimental studies. The measurements and computations of flows at lower velocities and temperatures are more tractable than those at high speed. However, advances in global time-resolved diagnostics at hundreds of kilohertz and current high-performance computing capabilities make scientific breakthroughs in the proposed area feasible. Because the impact forces approximately scale as the velocity squared, particle impacts in high-speed flows are likely to cause structural damage. Interactions involving liquid droplets are especially challenging because of flow-induced breakup, heating, and evaporation that alter the impact boundary conditions as a function of time. Adding to the complexity are the shock-wave / particle interactions, vortex shedding, and reverse shocklets that occurs when a particle enters the vehicle-induced shock layer. The erosion from solid and liquid hydrometeors and particulates can also produce surface roughness that initiate the flow instabilities responsible for laminar-turbulent boundary layer transition. Since existing computational models cannot capture these complex, multiscale finite-rate processes, high speed multiphase-flow / material interactions are currently estimated via component testing and empirically derived correlations. This program aims to improve the scientific understanding of the physical phenomena occurring in high-speed multiphase-flow / material interactions such as interfacial instabilities, shock / particle interactions, conjugate heat-transfer, phase change, rarefaction effects, and high-strain rate impact physics in the presence of aero-thermo-structural forcing.

Objective: The objective of this MURI is to understand and predict the coupled physical phenomena arising when solid particles or liquid droplets interact with high-speed flows (M>3) and solid surfaces. This involves the modeling of hypersonic multiphase flows and multiphase-flow / surface interactions including material response at high strain rate for erosion and material damage predictions. Conditions of interest include non-uniform supersonic and hypersonic flow-fields with shock layers and boundary layers. Novel experimental techniques to reproduce the critical physical phenomena and generate high quality validation data at relevant conditions are needed. This includes time-resolved measurements of velocities and state variables in both the gas, solid and liquid phase. Methods to measure stress waves inside the impacted material and track the temporal evolution of surface morphology are also needed.

Research Concentration Areas: Proposed research areas include but are not limited to: (1) Experimental methods, instrumentation, and diagnostics to generate and probe the relevant physical mechanisms and collect the data required for model validation; (2) Computational modeling of high-speed multiphase flows that capture interfacial instabilities, interactions with shocks and boundary layers, conjugate heat transfer, phase change, and rarefaction effects. (3) Computational modeling of multiphase-flows / surface interactions and in-depth material response at high-strain rate for material damage predictions; (4) Atmospheric science to characterize and predict the spatio-temporal characteristics and morphodynamics of hydrometeors and solid airborne particulates required to provide initial conditions for multiphase-flow / material interactions arising during atmospheric flight.

Anticipated Resources: It is anticipated that awards under this topic will be at an average of $1.5M per year for 5 years supporting no more than 5 funded faculty-student research teams.

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Topic 10: (ONR) Combining Disparate Environmental Data Into a Common Framework

Background: To maintain an operational advantage through information dominance, the Navy must bring together a multitude of data types to create a common operational picture. This information is used to make decisions that are expected to be superior by having the best possible situational awareness. However, blending information from different data streams into a common framework is not usually straight-forward. The available data is often a mix of remote sensing observations, *in situ* observations, climatological data, and predicted environmental fields, and it is not often clear how the different data streams should be combined to enable their exploitation to achieve mission goals. Typical Bayesian representations of the probabilistic accuracy of observation types are sometimes not appropriate for available observation types, and alternative methods are needed to combine the disparate information into a coherent understanding of the operational environment. This must be done in a way that incorporates the inherent uncertainties in the data to allow for the information to be utilized effectively to explore different courses of action and enable an informed decision.

One example of the difficulty in obtaining a useful situational awareness of the operational environment is the maritime Arctic, with sea ice being the critical parameter. At any time, there may be only a very limited number of *in situ* sensors in this region, though there is often a wide variety of satellite remote sensing data sets that provide observations with good spatial coverage at multiple resolutions. In addition to the direct and remote observations of the Arctic domain, there are also human-derived analysis products that provide some spatial information about a few key operational variables, such as maps of the sea ice edge or the presence of icebergs. If all of these disparate information sources were combined in an effective and efficient manner, the state of Arctic sea ice could be effectively characterized on a daily basis. This problem is offered as a prototype example, as useful information will include a mix of localized *in situ* sensor data with high fidelity but low coverage, high-resolution patches of satellite data with greater coverage but lower fidelity, coarse satellite data that covers the entire Arctic domain, and derived analyses that provide spatial context but limited descriptions of the environmental itself. New methodologies are needed to effectively combine these disparate data sources into a coherent picture of the Arctic maritime domain on a daily time scale.

Objective: The goal is to develop techniques that support the combination of disparate data sources into a common framework, using a multivariate approach that exploits the relevant information available in each data set while also accounting for varying degrees of fidelity and a robust ability to handle disagreements between information sources. A successful project would develop a formalism that goes beyond the traditional statistical approach to deal with the diverse and sometimes conflicting information, with this framework applied to the example of providing a daily characterization of the Arctic sea ice cover at high spatial resolution. The proposed approach should explore approaches that are well beyond simple multi-sensor data fusion techniques, and should consider the uncertainty and information content of each of the individual data sets that are incorporated into the overall synoptic depiction of the present state of sea ice in the Arctic environment.

Research Concentration Areas: Appropriate work under this topic may include but is not limited to research involving (1) techniques to characterize, combine, and minimize uncertainty in related-but-disparate data sets; (2) development of formal analytical frameworks that can be used to fuse together data sets with varying information content (e.g. Dempster-Shafer theory), and (3) novel algorithm development for existing and future satellite data sources. A successful proposal will incorporate contributions from investigators with expertise in mathematics, data fusion, information sciences, sea ice physics, and remote sensing.

Anticipated Resources: Awards under this topic will not exceed an average of $1.5M /year for 5 years, supporting ~6 faculty researchers. Exceptions warranted by specific proposed approaches should be discussed with the topic chief during the white paper phase of the solicitation.

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Topic 11: (ARO) Adaptive and Adversarial Machine Learning

Background: The success of autonomous cars on US roads has created excitement in the general population, and, in particular, the DoD community regarding potential breakthroughs by using Machine Learning (ML) and Artificial Intelligence (AI). Machine Learning, when used as an enabling technique in vision, planning, or knowledge representation, improves overall effectiveness; however, it can also be easily defeated by minute perturbations of the input or training data used. Concomitantly, it has been observed that ML-based systems fail badly when used in regimes that they are not trained under, for example, failure of vision algorithms under bad lighting - making domain adaptation (i.e., ability to adapt) as important as making systems robust to adversarial attacks. Given that ML based systems are used widely in critical applications such as autonomous cars, drones, banking, decision making in intelligence community, etc., it is critical to make such systems robust against corrupted training data, evasion attacks and unexpected inputs. A knee-jerk reaction is to ask for copious amounts of data in association with better statistical modeling. However, asking for (even) more data is a non-starter in DoD setting, making a neuro-inspired approach promising. After all, humans, in spite of their individual biases, generalize, reflect, triangulate, and fuse multimodal information to effectively deal with corrupted, incomplete, uncertain input (e.g., low lighting, perturbed frames in vision, misspelled words, and grammatically incorrect sentences); indeed, they deal effortlessly with never before seen situations too, by using context and semantics of tasks in addition to memory. Neuro-science models of attention, and vision, suggest a combination of goal-driven top-down procedure working in tandem with low-level data-driven process for efficient decision making and learning, in spite of conflicting, confusing and corrupted signals. Recent work at the intersection of Control Theory, Machine Learning and Formal Methods suggest that a neuro-science inspired approach to building robust and adaptive ML systems is feasible, and could potentially replicate human performance in dealing with corrupted, incomplete or uncertain input, while maintaining performance characteristics when adapting to new untested environments.

Objective: Create mathematical and algorithm development frameworks, that are application and implementation technique independent, to build robust and adaptive ML-based intelligent systems, with predictable properties and performance bounds, that are capable of generalizing, reflecting, and reasoning in a contextual manner.

Research Concentration Areas: Expertise is needed for: (a) developing abstractions, specifications, semantics, and counter-example guided exploration of state space of features and data; (b) construction of robust, resilient, model-driven systems that can learn, adapt, and reflect; (c) adaptation of theories on childhood learning and common-sense reasoning (adults are too complicated) to drive ML fusion of conflicting information; (d) bounding performance and reasoning about emergent properties of learning in ensembles; (e) experimentation in building AI systems to validate the proposed work; and (f) building software development frameworks for reflective, robust and resilient systems, by rapidly turning work of theorists to practice.

Anticipated Resources: It is anticipated that awards under this topic will be no more than an average of $1.25M per year for 5 years, supporting no more than 6 funded faculty researchers.

Note: Proposals are invited that include participation from Australian (AU) academic institutions; however, AU participation is not a requirement. In the case of proposals with AU participation, there still should be a single US primary institution and one PI submitting the overall proposal. Funding for the AU participation will be allocated separately by the AU government. Opportunities for Australian funding for such collaborative proposals are described at http://www.business.gov.au/ausmuri.

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Topic 12: (ARO) Axion Electrodynamics beyond Maxwell's Equations

Background: Classical electrodynamics based on Maxwell's equations has been the basis of radio, wireless, radar, RF/microwaves technologies. It provides a mathematical model unifying electricity and magnetism and is one of the cornerstones of modern physics. Recent advances, however, have predicted that for topological materials such as topological insulators (TIs) and Weyl/Dirac semimetals, orbital magnetoelectric coupling adds an axion term $\Delta L_{axion} = \theta(e^2/2\pi hc)\boldsymbol{E} \cdot \boldsymbol{B}$ to the Lagrangian that governs the behavior of the electromagnetic field. This modifies Maxwell's equations giving rise to a host of interesting novel electromagnetic effects. The most striking of these is the topological magnetoelectric effect in TIs, where an electric field generates a topological contribution to the magnetization in the same direction. Similarly, many effects in Weyl/Dirac semimetals, such as chiral magnetic effect and circular dichroism, can be expressed in terms of this axion electrodynamics formalism. These advances open the door for a new class of topological magnetoelectric device concepts in which simultaneous tuning of electrical and magnetic properties via electrical field can be achieved without electrical current dissipation. Current electric field tunable magnetoelectric devices rely on multiferroic materials. Despite decades of research, a room-temperature multiferroic material with robust ferroelectric and ferromagnetic orders is still lacking. Topological magnetoelectric materials can potentially overcome this. Intense research in the past decade has led to high quality topological materials in bulk and thin films with well differentiated topological electronic states. The materials' electromagnetic behaviors and opportunities for creating device structures with unique axion functions remain relatively unexplored. Recent measurements of quantized Faraday and Kerr rotation in TIs and the chiral anomaly in Weyl/Dirac semimetals confirmed theoretical predictions.

Further demonstrations of an axion insulator (magnetoelectric gapping of topological edge states) and the dynamic axion field (time-dependent electromagnetic effects due the axion term) also provide promising candidate platforms for realizing functional axion devices. Building on these initial developments, this topic aims to realize a new class of electric field tunable axion device concepts such as electric field switching of ferromagnets, voltage tunable magnetic inductors, filters, resonators and non-reciprocal devices without current dissipation through a cohesive, multi-disciplinary approach involving electronics, physics and materials.

The materials aspect of this topic is not aimed at the development of new topological materials, Weyl, photonic bandgap topological insulators, or otherwise, but rather the formation of pristine, atomic-level interfaces between (known) topological materials and non-topological materials, such that the axion term is not suppressed by chemical interactions, defects, or impurities. Likewise, emphasis is on managing the physics of the intertwined electronic and magnetic phenomena amid electrical contacts and other media necessary in a real, non-idealized environment. The phenomenological aspect is focused on observing and exploiting the axion term for unique magnetoelectric effects in these heterostructures: how magnetic properties can be controlled electronically and vice versa at levels and in ways that are not possible in traditional materials.

Objectives: To fundamentally understand axion electrodynamics in topological solid-state systems and demonstrate axion-based electric field control of both electric and magnetic properties.

Research Concentration Areas: Suggested research areas of interest include, but are not limited to: 1) Develop axion field theory and computation models of topological solid-state systems, e.g., topological insulators, Dirac/Weyl semimetals and their heterostructures, and explore unique electromagnetic phenomena enabled by axion electrodynamics; (2) fabricate high quality topological axion structures and create control interfaces to these structures; (3) Demonstrate device concepts with electric field control of both electric and magnetic properties enabled by the axion term in Maxwell's equations.

Anticipated Resources: It is anticipated that awards under this topic will be no more than an average of $1.25M per year for 5 years, supporting no more than 6 funded faculty researchers. Exceptions should be discussed with the topic chiefs during the white paper phase.

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Topic 13: (ARO) Engineering Endosymbionts to Produce Novel Functional Materials

Background: Biological systems produce materials that are highly ordered and shaped at scales from nano to macro, manage complex chemical pathways with stereospecificity, extract feedstock from atmospheric carbon and mixed waste, and take advantage of the power of exponential growth, all in ambient conditions with minimal waste. Biomaterials are created by insects, plants and animals, based on repeated periodic organic molecules such as carbohydrates and proteins.

Bioproduced photonic crystals, for example, are flexible and allow wavelength-specific displays without pigment. These displays can be beyond the human visual spectrum (e.g. UV light in butterfly wings, near-IR in chameleon skin) and dynamic (e.g. color change in the chameleon skin). So far, the eukaryotic organisms capable of producing such materials have resisted efforts to program them, presenting many challenges because of the complexity of their genomes and mechanisms for maintaining genetic stability. This project will explore the fundamental process of biosynthetic production of novel functional materials by using a eukaryotic organism controlled by a more easily and rapidly engineered prokaryotic endosymbiont for rapid, flexible, modular control.

Engineering of bacteria has reached a workable state of predictability and stability, but much of the processing machinery used by higher organisms to create complex structures and materials simply does not exist in these simple cells. Eukaryotic systems provide opportunities to realize more sophisticated products; however, these complex organisms present significant challenges to engineer and program. In a hybrid system, the best of both can be achieved: an engineered, prokaryotic endosymbiont controlling a eukaryotic host cell to produce materials of interest.

Rational design of biomaterials requires a multidisciplinary approach. Materials scientists will define the desirable characteristics for production, provide direction for biological work, and develop rapid-throughput tests for presence and characterization of organic materials. Biologists will develop the programmable endosymbiotic hybrid system and determine how to manage and control the production of desired bio-material. Suggested research areas include but are not limited to: (1) synthetic biology; (2) evolutionary biology; (3) material science; (4) optics and optical physics; (5) modeling and simulation.

Recent findings indicate the timeliness of this multidisciplinary approach. The role of dynamically tunable organic crystals has been described in both color change and thermal management in the skin of the chameleon. The requirements for stable intracellular symbiosis are under active study, including the creation of the first engineered obligate intracellular bacteria. Researchers are beginning to understand how intracellular parasites manipulate a host cell into carrying out the instructions of the parasite, and this forms the basis for engineering endosymbionts that can use those same mechanisms for a desired result. As an example of a potential strategy under this topic, structural tuning of chitin crystals is accomplished by varied size and spacing of chitin fibrils in butterfly scales. The rice blight endosymbiont produces a secreted chitin-binding and digesting complex which could be engineered as a chitin modification system to tune chitin crystals produced by a host-cell.

Objective: To develop a eukaryotic organism driven by a programmable prokaryotic organism, and to use the hybrid system to explore the creation of novel functional materials.

Research Concentration areas: Suggested research areas include but are not limited to: (1) investigation of endosymbiont survivability (2) genetic programming for materials synthesis; (3) exploration and characterization of biomaterials produced by eukaryotes; (4) synthetic biology programming principles for directing a eukaryotic host via an endosymbiont; (5) development of high-throughput screening systems for desired bio-produced advanced functional materials (such as photonic crystals with desired optical properties) to enable directed evolution and similar techniques; 6) modeling and characterization of the biosynthesized material.

Anticipated Resources: No more than an average of $1.25M per year for 5 years, supporting no more than 6 funded faculty researchers. Exceptions warranted by specific proposal approaches should be discussed with topic chiefs during the white paper phase of solicitation.

Research Topic Chiefs:
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Topic 14: (ARO) Information Exchange Network Dynamics

Background: The spread of the information in social media is highly correlated with its novelty relative to previous messages. Novelty of news can be measured in an information theoretical sense by, for example, its Relative Entropy with respect to previously consumed information. Relative Entropy is a measure of the difference between probability distributions representing the content of the incoming news and those of the previous news to which subjects were exposed. Assuming misinformation was generated to modify the perception of the ground truth, it would tend to have high Relative Entropy, thus novel. However, not all novel information is spread broadly or re-transmitted by individuals. Humans decide on whether and how to transmit information based on various factors which may include its novelty, as well as its context, relevance to the interests and to the value system of the individual, source, and provenance.

A possible model for this decision process could involve Bayesian updating of a probability distribution function relating to some of the factors listed above. Such a function may reflect opinions, values, and in general, what is important to the receiving party. Upon receiving a new message, a person will update that distribution function, using some action similar to Bayesian updating. In this model, the update could trigger a decision on whether and how to propagate the news. The virility of information spread is inherent to the outcome of the human cognitive process, which is central to this topic. There are various challenges in building a Bayesian formulation for information transfer to become knowledge updating. For example, if a message corresponds to a highly unlikely event whose source is not trusted, the person could ignore it, even though its "novelty" could be significant. Cognitive processes are known to occur at different time scales and do not always follow a smooth, continuous path. Human based experiments can be helpful in addressing some of these issues. For instance, current research indicates that decisions are influenced by the decisions made by others in one's network, and that limited attention allows for the spread of low quality information by reducing discernment. This MURI work should focus primarily on the cognitive and decision making processes that motivate information spread.

The cognitive processes which drive the propagation of information flow will involve research in experimental psychology, computer science, and information theory. Collective advancements in these disciplines will enable understanding of information flow dynamics, derive models to provide insight on how authentic and misinformation are propagated differently, and devise ways to quantify misinformation spreading. These cognitive models must be specified with mathematical precision to include boundary conditions, information transfer rates and limiters, control for knowledge topics, allowing for emergent topics, all within a network framework of diverse set of actors.

Objective: The objective of this MURI is to model the dynamics of cognitive processes over information networks for efficient information diffusion, controlling its veracity, and forecasting potential cognitive outcomes of these dynamics.

Research Concentration Areas: Suggested research areas will draw from the intersection of psychology, communication, computer science, network science, and information theory and include but are not limited to (1) models of psychological belief states as a function of knowledge space for individuals and collectives; (2) extend beyond current information processing models to include multidimensional aspects of knowledge, capacity for learning and retaining knowledge, and accounts for impacts of non-ergodicity; (3) causal cognitive models from human subjects' experiments; and (4) assessing veracity of information computations and their impact on human decision making processes.

Anticipated Resources: It is anticipated awards under this topic will be no more than $1.25M per year for 5 years, supporting no more than 6 funded faculty researchers. Exceptions warranted by specific proposal approaches should be discussed with topic chiefs during the white paper phase of solicitation.

Research Topic Chiefs:
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Topic 15: (ARO) Mathematical Intelligence: Machines with More Fundamental Capabilities

Background: Construction of error-free programs is empirically difficult, and error rates increase in line with their complexity. As a result, efforts to combine machine based verification with the human element are developing and experts are beginning to recognize that error proof machine generated programming is mandatory when zero tolerance in execution is required. Elements that will enable this advance are now emerging. In particular, a) Deep connections between the fields of topology, logic, and computer science, and physics theory have been rigorously established using higher category theory, a formalization of mathematical structure and its concepts which uses labeled, directed graphs to build objects and morphisms to go between those objects. b) The kinematics of a quantum system can now be mapped to oriented manifolds of topologies, data types in computer science, or propositions in logic. c) Similarly, the dynamics of quantum systems can now be described in the language of topology in quantum field theory, algorithms in computing, proofs or refutations in logic, or as processes in physics. These correspondences are achieved by implementing synthetic topologies where spaces are basic objects and the presence or absence of holes determines continuity of paths. In category theory, morphisms between these object spaces, and morphisms between morphisms iteratively form arbitrary hierarchies. d) It is now recognized that in quantum physics, the first few levels of such a hierarchy correspond to the field, Hilbert space, and the linear operators respectively. The unitary operators which can encode algorithms from this operator level onwards create arbitrary levels of hierarchies constructed similar to abstract objects of a C++ program. At such higher dimensions, geometric, topological, or physical intuition may become infeasible, forcing one to rely on algorithmic approaches, and it is mandatory that these algorithms are developed in a certifiably correct way. This topic will develop this science of processes as the basis for building powerful machines that reason at a fundamental level, seamlessly mapping problems between the four domains. This will enable, for example, studying the quantum stochastic processes describing open system evolutions as continuous paths on topological spaces or vice versa. In a computational sense, this will enable a consistent codification of morphisms across a wide variety of disciplines (for example non-relativistic, relativistic, and topological quantum field theories) and thereby establish the foundation for automated reasoning. This will ultimately enable mathematically intelligent (MI) machines equipped with deduction, induction, and logical inference, and basic research involving this exchange of tools developed over centuries in the four fields will enable capabilities for generating new insights that are certifiably correct.

Objective: Develop the new science of iteratively-constructed logical deduction in the context of quantum field theories (non-relativistic, relativistic, and topological) for quantum information processing (QIP) and develop its basis as a foundation for certifiable automated reasoning.

Research Concentration Areas: These include, but are not limited to, a unified approach to: 1) Develop topological quantum field theory based information processing that is certifiably correct; 2) Develop the necessary understanding to apply higher category theory to relativistic quantum field theory with a QIP perspective; 3) Develop a quantum stochastic differential equation description of 'homotopy quantum fields' (non-relativistic) to describe analog quantum computation; 4) Create a language to describe and verify the correctness of quantum protocols; 5) Create formal structures for algorithms in quantum computing that are based on the three quantum field theories.

Anticipated Resources: $1.25M/year for 5 years, supporting no more than 4 faculty researchers. Exceptions warranted by specific proposal approaches should be discussed with topic chiefs during the white paper phase of solicitation.

Research Topic Chiefs:

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Topic 16: (ARO) Quantum State Engineering for Enhanced Metrology

Background: Assured position, navigation, and timing is a high priority, especially for autonomous platforms. For platforms to maintain accurate knowledge of their position, orientation, and altitude during missions, the uncertainty errors accumulated over time have to be constrained by external aides, such as GPS. When GPS is absent or compromised, exquisite inertial sensors with high performance and low uncertainty in measurement may maintain sufficient accuracy. If the uncertainty can be made small enough, the error in position is still manageable after long periods of accumulation. Quantum systems – especially atomic based systems – are a promising candidate due to their demonstrated precision. Unique to quantum systems is the ability to exploit special states such as squeezed states, number states, NOON states, cat states, and recently superpositions of maximally different energy states, which demonstrate metrology beyond what is possible classically. However, two important questions about quantum sensors remain: (1) Can special quantum states be realized that push the performance of these sensors to the fundamental limit? (2) Can these systems be engineered such that their exquisite sensitivity is constrained to what one intends to measure? Often successful demonstrations rely on isolation and minimizing unwanted interactions. Surprisingly, recent experiments have shown that certain engineered interactions can lead to increased correlations that enhance sensitivity and protect these special states from unwanted noise. There is a natural tension in designing a system that is incredibly sensitive and ensuring that the sensitivity is dominated by the quantity desired to measure. There is a scientific gap that needs classical engineering solutions applicable to quantum challenges. In particular, development of chip-scale atomic clocks (CSAC) has indicated simple engineering approaches such as geometrical scaling are not sufficient for preserving quantum state sensitivity. Recent results in engineering interactions with dissipative baths may provide a reasonable path for both realizing highly correlated quantum states and ensuring these states can maintain high performance when coupled to classical systems.

Objective: The purpose of this MURI is to investigate and develop methods that explore quantum correlations and special states to enhance metrology, improve sensitivity, achieve fundamental uncertainty limits in different ways, and integrate these states with thermal reservoirs and strong system design to mitigate decoherence. In addition this MURI will advance concepts analogous to classical engineering at the quantum/classical interface, while expanding the scientific area of engineered quantum states.

Research Concentration Areas: Possibilities include: Develop and exploit quantum correlated systems to enhance metrology and reduce measurement uncertainty to the fundamental limit, while demonstrating insensitivity to unwanted noise. For example (1) Investigate protocols in driven systems beyond the SQL; (2) Exploit special quantum states, e.g., squeezed, number, cat, NOON, and general entangled states such as superpositions of maximally different energy states, to demonstrate metrology beyond SQL; (3) Devise engineering and control methods that constrain the sensitivity of quantum systems toward intended measurements and isolate unwanted noise; and (4) Investigate driven systems, interactions with dissipative baths and schemes to control de-phasing.

Anticipated Resources: It is anticipated that awards under this topic will be no more than an average of $1.25M per year for 5 years, supporting no more than 6 funded faculty researchers. Exceptions warranted by specific proposal approaches should be discussed with the topic chief during the white paper phase of the solicitation.

Research Topic Chief:

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Topic 17: (ARO) Solution Electrochemistry without Electrodes

Background: Traditionally when we think of electrochemistry we image a system where electron transfer occurs at an electrode surface. In these systems the electroactive species interacts with the electrode and this interaction has an effect on electron transfer. What new electrochemistry is possible with free electrons in solution? In the 1960's pulsed radiolysis was developed and utilized by physicists and chemists to generate solvated electrons in solutions and to characterize their reactions with compounds. More recently surface plasmon decay in metallic nanoparticles coupled with light and atmospheric plasmas have been used to generate electrons and inject them into solutions. All three techniques generate electrons with different initial energy distributions and concentrations of other activated species. For example, in plasma driven systems not only are energetic electrons generated but so are positive ions and uncharged species. To date, very little research has been dedicated to using surface plasmon based systems to drive solution electrochemical reactions. A few reactions such as water splitting, ethylene oxidation, and citrate oxidation have been studied. However, in most cases the reactant has been attached to the nanoparticle surface so solution electrochemistry has not yet been explored. In the case of plasma driven systems recently silver nanoparticles have been synthesized through solution reduction of silver salts.

There are multiple drivers for this MURI program. First, in the last several years multiple new methodologies have been developed to inject energetic electrons into solution. We need to explore additional new methodologies and the conditions to transiently and continuously generate electrons while controlling their energy, flux, and concentration. In addition, electron penetration depth, mechanisms of relaxation (<1 picosecond), and solution lifetimes (100's of nanoseconds) need to be characterized. Second, novel electrochemistry and electrosynthesis utilizing energetic electrons with tunable energies, that are not accessible at solid electrodes, need to be explored including electrosynthesis of novel nanomaterials. Third, theory and computational modeling of electron generation, injection into solution, and relaxation need to be developed. For example, in the surface plasmon based system the theory for short time dynamics, and the effects of particle geometry and material need to be described.

Objective: The objective of this MURI is to explore and understand electrochemistry between electrons that have been generated by methods such as: atmospheric plasma, surface plasmon, or pulsed radiolysis and solution species. This effort is focused not only on controlling generation of electrons, but also characterization of their energies and lifetimes including electron penetration and diffusion to solution species, as well as novel solution electrochemistry and electrosynthesis. Electrochemical studies should take advantage of the lack of an electrode interface and the unique electron energies and energy distributions available using the aforementioned electron generation techniques.

Research Concentration Areas: Areas of research may include but not limited to: (1) Theoretical efforts to calculate and model electron generation, equilibration of solvated electrons, and electron transfer reactions; (2) Synthesis of materials and morphologies capable of generating electrons with controllable energies; (3) Novel methods of generating solvated electrons; and (4) Solution electrochemistry using generated energetic electrons.

Anticipated Resources: It is anticipated that awards under this topic will be no more than an average of $1.25M per year for 5 years, supporting no more than 6 funded faculty researchers. Exceptions warranted by specific proposal approaches should be discussed with the topic chief during the white paper phase of the solicitation.

Research Topic Chief:
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Topic 18: (ARO) Stimuli-Responsive Mechanical Metamaterials

Background: Metamaterials research has categorically demonstrated the potential for micro-architected materials to surpass the intrinsic properties and functionality of natural and conventional materials. Metamaterials now exhibit a range of novel electromagnetic, acoustic, or mechanical phenomena such as negative bulk properties (negative Poisson ratio, compressibility, or refractive index), advanced wave tuning (attenuation, guiding, and cloaking), as well as topological invariances and protection. Interestingly, most examples of exceptional functionality stem from sub-unit architectures exceeding micrometer length-scales, fixed lattice topologies, and chemically inert material constituents. If such remarkable properties manifest within essentially static and passive structures, what new behaviors and properties might arise should metamaterials instead be dynamic and chemically active? Moreover, what new functionality might arise should sub-unit architectures exhibit nanoscale structural complexity with stimuli-responsive constituents and distributed chemical triggering? Of particularly keen interest is the impact on mechanical properties and dynamics.

Several recent and pioneering breakthroughs suggest a new frontier of active metamaterials with precise and dynamically tunable properties is within reach. For example, nanomaterial assembly research has achieved order-of-magnitude advancement from micrometer sub-unit architectures to nanoscale supramolecular superlattices. Researchers have demonstrated colloidal single crystal synthesis with three-dimensional patterns of ordered nanoparticles as well as nanomaterial assembly onto surfaces with systematically controlled three-dimensional periodicity. The importance of interfacial phases in nanocrystalline materials has led to computational and characterization tools for their study. Additionally, notable advances in distributed chemical triggering mechanisms now enable mechanical property tuning by coupling hierarchical supramolecular assemblies to specified external inputs. These breakthroughs open doors to fabricating stimuli-responsive mechanical metamaterials with unprecedented architectural control. However, realizing the utmost potential for rationally designed active metamaterials will require further research on the role of interfacial phases as well as pathways for integrating modern understanding of metamaterial wave dynamics and topological mechanics.

Objective: The objective of this MURI is to create stimuli-responsive mechanical metamaterials with precise nanoscale interparticle, interfacial, and functional control. In particular, research should focus on novel topological effects as well as controlled and reversible changes in wave dynamics when stimulated by chemical inputs.

Research Concentration Areas: Suggested research areas include, but are not limited to: (1) Theoretical and computational methodologies capturing essential structure-function-stimuli relationships that enable predictive understanding of targeted nano-architectures and interfacial phase dynamics; (2) Experimental synthesis and characterization techniques for dynamic structural control (e.g. stimuli-responsive interparticle separation) as well as interfacial phases with consistent and measurable responses to external stimuli; (3) Novel precision measurement of desired mechanical properties at the constituent level, at the unit-cell level, or at selected limited locations and interfacial boundaries; (4) Control of chemo-mechanical interactions exploiting topological properties for bulk mechanical property changes or interfacial phase transformations; (5) Advanced metamaterial-enabled tailoring of the transmission, absorption, filtering and guiding of waves and mechanical loads (e.g., parity-time symmetry, coherent virtual absorption, non-reciprocity and directional gain, active and tunable topological protection).

Anticipated Resources: No more than an average of $1.25M per year for 5 years, supporting no more than 6 funded faculty researchers. Exceptions warranted by specific proposal approaches should be discussed with topic chiefs during the white paper phase of solicitation.

Research Topic Chiefs:
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Topic 19: (AFOSR) Machine Learning and Physics-Based Modeling and Simulation

Background: Numerical simulations have become an essential tool in the analysis, optimization and design of current and future aircraft, materials, rockets and other engineering and physical systems. Progress in modeling and simulation of increasingly complex and large physical systems has been possible by leveraging advances in both computational hardware technology and numerical algorithms. These simulations are principally based on numerical approximations of the equations (usually PDEs) that capture most of the physics of these systems. In recent years more experimental data have become available in situations where these PDE models do not exist, are unknown, or when multi-component, multi-physics paradigms cannot adequately describe the total system behavior. Recent advances in Machine Learning (ML) techniques, especially deep learning (DL), for processing large amounts of high dimensional data (e.g. imaging, natural language processing, bio-molecular pathways and drug discovery), bring the potential to use ML in connections with discovery of models, and/or the detection of important physical features and their functional relations, for very complex physical systems. However, the use of the ML techniques and their implementation on neural networks (NN) require fundamental understanding of how and why these algorithms work, and what is the proper architecture to give reliable and robust predictions. A co-design approach of proper representations, algorithm design, and topological organization of the NN could help advance the field on a rigorous mathematical foundation. Theoretical challenges also include how to use small, sparse data sets obtained by costly experiments or simulations as training datasets, how to impose physical constraints, how to achieve stability and robustness with respect to perturbations and training errors, and how to incorporate uncertainty quantification with respect to the data parameters, representations, and physical models.

Objective: This MURI aims at a rigorous, comprehensive approach to create ML algorithms and NN architectures for model extractions of complex physical systems. These exhibit non-linear, multi-scale high-dimensional dynamics that make their high-fidelity simulation challenging. The new ML techniques will analyze data to supplement the limited or uncertain PDE-based modeling in order to gain better physical insights, towards the discovery of physical models. Examples of such problems include fluid-structure interactions (at large deviations), turbulent combustion or plasma, chemical or bio-molecular processes, or material properties and dynamics, but many other candidate problems are potentially acceptable, depending on their modeling and computational complexity. The approach should include a strategy that includes choices of mathematical representations and parameters to minimize training costs, incorporation of measurements as "verified" data points, and contextual constraints known from the knowledge of the physical system at various levels of precision (e.g., conservation laws and bounds). The approach should also handle stochastic inputs, for incorporating uncertainty quantification in the modeling aspects, and offer an appropriate validation strategy.

Research Concentration Areas: Potential research directions include, but are not limited to; hierarchical and structure-preserving projections, geometric information theory, high-order manifold reconstruction, optimal transport theory, constraint learning, multi-scale modeling, Gaussian process regression, Bayesian inference and meta-learning. This MURI is expected to leverage the collaboration of researchers from multiple communities, e.g. optimization, machine-learning, computational science, and domain experts, to properly and comprehensively address the proper formulation and solution strategies for the non-convex optimization, inference, stochasticity, and architecture design problems, as well as the particular challenges of data sparsity, computational cost and validation from the chosen applications.

Anticipated Resources: It is anticipated that awards under this topic will total an average of $1.5M per year for 5 years, supporting up to 6 faculty researchers.

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Topic 20: (AFOSR) Fundamental Design Principles for Engineering Orthogonal Liquid-Liquid Phase Separations in Living Cells

Background: Physical barriers and compartmentalization (such as organelles with lipid membranes in eukaryotes) are critical in all living systems to control local concentrations of molecules for specific function (e.g. lysosomes for degradation), sequester toxic chemical and radical species (e.g. mitochondria, chloroplasts), and control access (e.g. nucleus). There have been recent discoveries of a number of intracellular processes that utilize ***transient*** liquid-liquid phase separation as a way to sequester and/or compartmentalize specific molecules without membranes (1). A number of proteins (some intrinsically disordered) have been shown to trigger formation of phase-separated droplets implicated in a number of neurological disorders such as Alzheimer's Disease (2). It has been speculated that normal DNA-chromatin organization may also entail phase-separation mechanisms (3). Specific RNA sequences with large numbers of repetitive sequence units (implicated in Huntington's disease and ALS) are shown to trigger similar reversible liquid-liquid phase transitions (4). Phase separation is also basis for the dynamic photonic responses seen in cephalopods. The mechanistic understanding of nucleic acids or proteins that can trigger phase transitions reversibly may provide a potential pathway to design transient synthetic molecular factories that could be used for cell-based material synthesis. Recent advances in CryoEM (electron microscopy) and CryoET (electron tomography) allow visualization of 3D intracellular structures including angstrom-level biomolecular interactions that may be involved in formation/destruction of these membrane-less compartments.

Objective: The goal of this topic is to elucidate natural mechanisms utilized by cells to effect intracellular phase separation and to exploit these design principles to enable improved biosynthesis of desired products by engineering orthogonal liquid-liquid phase-separated molecular factories or membrane-less compartments in living cells.

Research Concentration Area: Research concentration areas include, but are not limited to the following areas: 1) discover fundamental mechanisms and design principles behind dynamic liquid-liquid phase separations in eukaryotic cells, including but not limited to understanding how intrinsically disordered proteins, and/or specific DNA or RNA sequences may play a role in mediating these transient molecular structures; 2) discover the design principles for spatiotemporal control including feedback mechanisms involved in these transient structures; 3) apply these principles and synthetic biology tools to demonstrate orthogonal liquid-liquid separation systems in living cells for material synthesis; 4) develop high fidelity models to capture the natural dynamic processes and to guide designing of orthogonal spatiotemporally-controlled membrane-less compartments.

Anticipated Resources: It is anticipated that awards under this topic will be no more than an average of $1.5M per year for 5 years, supporting no more than 6 funded faculty researchers. Exceptions warranted by specific proposal approaches should be discussed with the topic chief during the white paper phase of the solicitation.

Research Topic Chiefs:
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Topic 21: (AFOSR) Modeling, Prediction, and Mitigation of Rare and Extreme Events in Complex Physical Systems

Background: By definition, rare and extreme events have low probability of occurrence, but with potentially catastrophic consequences, so that their detection and prevention in complex and multiscale systems is critical to the DoD and to society at large. These occur in wide-ranging applications such as materials science, space weather, biology, medicine, oceanic and atmospheric science, economics, geophysics, etc. Their studies have been done either from the statistical point of view (within large deviation theory and extreme value theory) or from dynamical systems theory, investigating mechanisms that lead to non-linear cascades, (e.g. amplification across length and time scales, including global bifurcations and bursting orbits). However, the underlying dynamical model in many systems with rare events is also stochastic (e.g., chemical reactions, protein aggregations, or nucleation events), requiring the combination of the statistical and dynamical points of view, with potentially simultaneous benefits. Unfortunately, existing methodologies that analyze and predict these events are either computationally prohibitive for the high-dimensional systems of interest or are only effective for low-dimensional dynamics and cannot capture the large-scale, nonlinear of interconnected systems of interest to the DoD. In order to provide theoretical breakthroughs, a unified mathematical framework for rare & extreme event predictions is needed. This general framework may combine techniques for stochastic processes, sampling methodologies, complex network theory, reduced order modeling, but also calls for innovative, paradigm-changing ideas. It should also be able to leverage multiple data types, resolution, computations and/or measurements, and take into account the computational resources required for solving the rare event problem in practical times. Purely data-driven approaches will not be adequate, as data samples are too sparse to yield all the information needed to accounts for event precursor detection and prediction.

Objective: This MURI aims at a comprehensive mathematical approach to predict and mitigate rare & extreme events for a wide variety of multi-scale physical systems. It should be able to efficiently compute the long-time macro-/meso-scale evolution, e.g. using a reduced-fidelity model, while simultaneously capturing the critical information for accurately evaluating the potential for generation of rare/extreme events. Of particular interest are problems involving dynamical and physical systems evolving on complex networks, whose topologies are themselves subject to complex and stochastic dynamics. In addition, the approach should help determine control mechanisms to mitigate the potential for rare events, e.g. for risk-aware design optimization. While the expansion and combination of novel but existing approaches may be justified, new mathematical theories can also be appropriate. The approach should be validated on a relevant problem of sufficient complexity depth, while also demonstrating its potential for generality. Material failure will provide a targeted application, but the choice of physical systems is left to the proposer, as long as the problem shows sufficient complexity and the characteristics of non-linear, cascade effects leading to sudden extreme events (e.g. cracking, delamination; metals, composites; natural or geo-physical materials…). A second targeted application choice is left to the proposer, but must be sufficiently different from the first, with preference given to systems on networks.

Research Concentration Areas: A combination of innovative methods is needed to deal simultaneously with the prediction of rare events, and the long-time evolution of the system as a whole. Potential approaches include, but are not limited to; network theory, non-linear dynamics, statistics, stochastic processes, risk-aware optimization, machine learning, equation discovery, causality analysis, and reduced order modeling. High-fidelity simulations can be used to provide the deterministic environmental setting and validation, and/or refine the long time evolution. Incorporation of variable resolution and uncertain experimental observations is also useful.

Anticipated Resources: It is anticipated that awards under this topic will total an average of $1.5M per year for 5 years, supporting up to 6 faculty researchers.

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Topic 22: (AFOSR) Fundamental Limits of Controllable Waveform Diversity at High Power

Background: Recent advances in materials science, computation, and theory have enabled dramatic reductions in the size of high power (100 MW through multi-GW) beam-driven microwave sources [1,2]; however, while some sources allow for some degree of frequency tunability without mechanical reconfiguration, most don't approach the waveform frequency and amplitude diversity provided by their lower power amplifier counterparts [3]. Multiple scientific and technical challenges limit the bandwidth and ability to impose arbitrary waveforms on an output signal in extremely high power regimes where nonlinearities arise. These interactions are well-understood in sub-relativistic beam amplification, however, at high power the interplay of non-ideal beam properties imposed by the requirement for highly energetic (relativistic) electron beams, coupled with resulting nonlinear space charge effects within amplifiers, requires a better understanding to enable the desired broad bandwidth amplification and waveform control. Additionally, plasma formation in high field regions and in regions where the beam may directly interact with surfaces represents a significant challenge. While these plasmas may be reasonably well confined near material structures by strong magnetic fields, they do impose nonlinear boundary conditions, which may narrow or eliminate regimes in which amplification is possible.

A better understanding of the interaction of these near-surface plasmas is critical to defining the limits of amplification and the transition to oscillatory behavior in high power regimes, a transition that leads to a reduction in the bandwidth and ability to control or modulate the signal. A better understanding of these phenomena would also help elucidate whether new exploitable mechanisms of waveform control become accessible GW power levels. A successful proposal should ideally address the scientific challenges discussed and seek to answer questions such as: How and when does waveform control of an amplifier converge to that of an oscillator? What metrics are appropriate to describe amplification processes in these regimes? Do amplification processes at extreme power levels necessarily impose fundamental limits on the fidelity of amplified waveforms compared to what is achievable in non-relativistic regimes?

[1] J. Benford, et al., "High Power Microwaves, 3rd Ed.," CRC Press, (2015).
[2] J. Lehr, et al., "Foundations of Pulsed Power Technology," IEEE Press, (2017).
[3] A. Gilmour, "Klystrons, Traveling Wave Tubes, Magnetrons, Crossed-Field Amplifiers, and Gyrotrons," Artech House (2011).

Objective: The objective of this MURI is to advance the fundamental understanding amplification processes in energetic regimes, beam-wave interaction, nonlinear material interactions in extreme electromagnetic environments, and plasma formation as they impact limits to waveform diversity at extreme power levels. These issues should be addressed theoretically, computationally, and experimentally to explore the limiting physical processes specific to HPM amplification.

Research Concentration Areas: Suggested research areas include: (1) plasma physics and electromagnetic theory/modeling to understand physical processes, such as beam-wave interaction, self-oscillation, and other instability phenomena; (2) high quality electron beam generation and propagation; and (3) novel EM designs and materials for broadband, high power matching.

Anticipated Resources: It is anticipated this topic requires approximately $1.5M per year for 5 years, supporting no more than 5 funded faculty researchers. Specific approaches requiring exceptions must be discussed with topic chiefs during the white paper phase of the solicitation.

Research Topic Chiefs:

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Topic 23: (AFOSR) Full Quantum State Control at Single Molecule Levels

Background: Full quantum state control of ultracold atoms has led to atomic clocks for exquisite timekeeping, atom interferometry for sensing, and quantum simulation of complex condensed-matter systems. Atoms can be cooled, trapped, transported, detected and imaged at single particle levels, and be skillfully manipulated between quantum states with high fidelities. Following these extraordinary advances in atoms, in the last decade researchers have demonstrated spectacular progress in the cooling and trapping of various molecular species, including laser cooling to sub-microKelvin temperatures and trapping using magnetic, electric or optical fields. Single molecules can even be created from two laser-cooled atoms using optical tweezers and photoassociation. Molecules, unlike atoms, can possess the combination of strong, long-range dipole-dipole interactions, numerous degrees of freedom due to vibrational and rotational motion, and quantum states with long-lifetimes. This unique combination in a wide variety of molecules can be leveraged for invaluable applications including quantum simulation, controlled chemistry, and precision measurements. However, for these opportunities to materialize, full quantum state control of ultracold molecules is absolutely essential.

Fortunately, recent progress in preparing and manipulating molecules indicates it is possible to achieve this lofty and challenging goal. In 2010, scientists created long-lived, chemically stable molecules in their absolute ground states and controlled the hyperfine sublevels (Ospelkaus *et al*., *Phys. Rev. Lett.* 104, 030402 (2010)). Subsequently, Will *et al*. (*Phys. Rev. Lett*. 116, 225306 (2016)) showed they could transfer an entire ultracold molecular ensemble to the first rotationally excited state, and revealed that the excited state can have long collisional lifetimes of a few seconds, comparable to those in the ground state. Even more recently, Chou *et al*. (*Nature* 545, 203, (2017)) mapped quantum information between an atomic ion and a molecular ion using quantum logic spectroscopy to prepare and detect the quantum mechanical state of the molecular ion. To develop full quantum control of molecules and unlock its vast potential, now is the optimal time to launch this concerted, multidisciplinary effort that pulls from theory and experiment in atomic and molecular physics, quantum chemistry, and quantum control.

Objectives: The aim of this MURI topic is to (1) theoretically understand and experimentally realize full quantum state control at single molecule levels, including well controlled initiation, manipulation, and readout of quantum states, as well as development and manipulation of tunable and strong, long-range dipole-dipole interactions; and (2) exploit this power of coherent control to understand the quantum physics and chemistry of molecules and complex quantum states and dynamics, as well as discover new fundamental phenomenon.

Research Concentration Areas: Suggested research areas include but are not limited to: (1) development and implementation of effective theories and accurate computational modeling methodologies aimed at describing properties in molecules in which quantum processes or entanglement are important, (2) experimental realization of controlled quantum state initialization, dipole-dipole interactions such as entanglement of molecules, and fast readout of quantum states, (3) control of coherent as well as dissipative processes, and (4) comprehensive analysis of how full quantum state control of molecules could be leveraged for uses such as quantum simulation, chemistry, and precision measurements.

Anticipated Resources: It is anticipated that awards under this topic will be no more than an average of $1.5M per year for 5 years, supporting no more than eight (8) funded faculty researchers. Exceptions warranted by specific proposal approaches should be discussed with the topic chiefs during the white-paper phase of the solicitation.

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Topic 24: (AFOSR) Constructive Mathematics and Its Synthetic Concepts from Type Theory

Background: The symbiosis of Homotopy Type Theory and Univalent Foundations is arguably the most exciting field emerging from the interface of mathematics, computer science, and logic in recent years. They equip and enrich dependent type theory, a foundation of (functional) programming languages and proof assistants, with homotopical content and a notion of invariance under type equivalence from which quotient types and higher inductive types can be constructed. Grounded on these novel type structures and type formers, a new foundation for mathematics based on the constructive principles, in stark contrast with the traditional foundation for mathematics rooted in set theory and first-order logic, is being mapped out. In principle, constructive proofs of mathematics can formally be carried out on computers with infallible details; algorithmic procedures for finding mathematical solutions can be constructed without merely resorting to existence assertions. At the same time, novel *synthetic* structures of mathematics (e.g., synthetic homotopy theory, synthetic differential geometry) have naturally arisen from new type constructions and logical modalities. Despite the accumulation of fresh, promising results in these directions, there are still deep, unresolved issues that need longstanding exploration. For instance, it is highly desirable to have a type system with these properties: decidable type checking, efficient computation of topological invariants such as homotopy groups, computational justification of the univalence axiom and higher inductive types. Relating the synthetic notions to their conventional counterparts in the mathematics literature also poses interesting questions.

Objectives: This topic seeks the development of higher structures, their syntax and semantics, associated with variants of Homotopy Type Theory, which would lead to synthetic theories and new foundations of mathematics based on types. Testing these concepts on existing proof assistants and collaboration with unfunded international researchers are highly recommended, but not required.

Research Concentration Areas: Suggested research areas include but are not limited to: (1) Higher inductive types with higher coherence operations, towards a synthetic theory of higher categories and foundations of mathematics; (2) The viability of using Homotopy Type Theory and Univalent Foundations as an internal language of higher topoi; (3) Monadic and comonadic modalities in type systems in consideration of synthetic differential geometry, topology, and other synthetic approaches to mathematics; (4) Formalization of synthetic mathematics in proof assistants; (5) Understanding the relationships between synthetic and traditional mathematical concepts; (6) Construction of a normalizing type system equipped with higher inductive types in which type-checking is decidable; (7) Higher structures of types and their roles in programming languages, including probabilistic programming on arbitrary measure spaces; (8) Proving new mathematical theorems by leveraging ideas from type systems and synthetic mathematics; (9) Exploring new models, and their internal languages, of type theory and Univalent Foundations.

Anticipated Resources: It is anticipated that awards under this topic will be no more than an average of $1.5M per year for 5 years, supporting no more than 6 funded faculty researchers. Exceptions warranted by specific proposal approaches should be discussed with the topic chiefs during the white-paper phase of the solicitation.

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Topic 25: (AFOSR) Weyl Fermion Optoelectronics

Background: Topological phenomena and topological materials have inspired new discoveries that may have important impacts on DoD and commercial applications. Weyl fermions are massless quasiparticle excitations in so-called Weyl semimetals (WSMs), such as TaAs and NbP, with band structures exhibiting zero energy gap crossings called Weyl nodes. These nodes come in pairs, separated in momentum space, each associated with a specific positive or negative chirality. They are connected through the crystal boundaries by topological Fermi arc surface states. Weyl nodes are sources and sinks of Berry curvature, which mathematically serves as a momentum-space form of a magnetic field and which provides a fundamentally new channel for current to flow through the WSM; a mechanism that has no counterpart in traditional metals or semiconductors. This new channel provides a more stable transport of charge than electrons, the principal carriers in modern optoelectronics. A host of challenging questions arise owing to the exotic behavior of Weyl fermions. This topic seeks answers to fundamental questions such as can the unique bulk and surface band structures of WSMs be exploited for novel phenomena and novel electronic and optoelectronic device concepts? And, by including nonlinearities and quantum effects, can better ways of controlling and engineering light and its interaction with matter be identified and exploited? The topic focuses on characteristics such as the chiral current and the unique surface and bulk band structures that are only found in WSMs. WSMs exhibit exceptionally high electron mobilities, which could lead to faster, lower-energy circuits and to new types of quantum computing, ushering in an era of "Weyltronics." Parallel electrical and magnetic fields can break the apparent conservation of chiral charge due to the chiral anomaly, making WSMs—unlike ordinary nonmagnetic metals—more conductive with increasing magnetic field strength. There are many opportunities to explore photonics in this new regime—for example, by including nonlinearities, electromagnetic vorticity, and quantum effects—that could lead to better understanding of the full scope of possibilities for new classes of revolutionary opto-electronic devices, and the required material properties.

Objective: The objective is to explore Weyl semimetals and determine if the novel physics such as the chiral current, Fermi arcs, and Weyl nodes can be exploited to devise meaningful phenomena and functions, such as amplification, switching, and detection, especially in the optoelectronics and electronics domains. Thin films and bulk materials are both of interest. This MURI will also seek new device structures and characterization techniques to enable further understanding of the unique properties of these materials.

Research Concentration Areas: Suggested research areas include, but are not limited to: (1) theoretical studies of Weyl fermion transport, including understanding of differences between Type I and Type II WSMs; (2) design and growth of thin films and bulk materials; (3) characterization by optical, electrical, magnetic and structural means; and (4) concepts to exploit WSMs for unique phenomena and functions in photonic, electronic, and quantum devices.

Resources: Awards under this topic aim at multidisciplinary teams at the $1.4 M to $1.6M/year level for five years, supporting no more than seven (7) funded faculty researchers.

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Topic 26: (AFOSR) Mechanisms of Ice Nucleation and Anti-Icing Constructs

Background: The fundamental nucleation and growth mechanisms of liquid water crystallization into solid ice are complex processes with numerous steps at the molecular and nanoscopic scales. Methods to mitigate or inhibit these phenomena and improve on traditional anti-freeze agents, for instance to prevent water build up on surfaces or the growth of clusters of large enough critical size so that crystallization does not propagate throughout the material, are of technological interest for applications. These applications can include ice accumulation in aerospace vehicles, cryopreservation of cells and tissues, food processing, or ice-templating the morphology of materials. Antifreeze proteins, which permit fish, insects, bacteria, and plants to live in cold climates, provide an example of preventing growth of nanoscale ice crystals into larger structures thereby preventing a bulk phase transition. A better understanding of the mechanisms and the forces controlling ice nucleation, and how certain materials or structures can interfere with these phenomena, can lead to new strategies and technologies for anti-icing and deicing. Optimal molecules, polymers or designed de novo peptides can be developed to provide anti-icing agents which interact with nascent ice nanocrystals to prevent large scale ice formation. However, there are many challenges to performing simulations of ice nucleation, growth, or related phenomena, because of the multiscale nature of the problem. Since nucleating systems are thermodynamically metastable, small perturbations can have quite large consequences and chemical accuracy of less than 1 kcal/mol can be required in calculations to elucidate the reaction networks leading to critical clusters. Additional methods are needed to model the weak surface-ice interactions, interfacial electric fields, and the role of anti-icing agents which can influence binding and affect the network topology to disrupt long-range growth. The rare-event dynamics may also require simulations over the long time-scales inherent in the problem. High accuracy calculations coupled with coarse-grained simulation methods are beginning to shed light on ice nucleation mechanisms.

Experimental methods are now also being developed to probe the critical clusters and reaction networks involved in ice nucleation. De novo peptide design is also at an inflection point and ready to make important progress. Therefore, it is timely to put forward a concerted multidisciplinary effort on this topic since experimental techniques, theoretical simulations, and molecular design methods are now ready to contribute to a concerted multidisciplinary effort on this topic to understand nucleation processes and improve anti-icing approaches.

Objective: The objective of this program is to use experimental and theoretical methods to advance the fundamental understanding of ice nucleation and growth mechanisms and develop approaches or constructs that will optimally disrupt ice formation. The mechanistic effects of anti-icing agents at a molecular level should be determined, and from this understanding, new systems developed to improve anti-icing behavior. This program can include understanding how systems such as antifreeze proteins bind to critical ice nuclei and disrupt large-scale ice crystallization, and demonstration of antifreeze activity in rationally designed materials or biomaterials, including de novo peptide design.

Research Concentration Areas: Suggested research areas include but are not limited to: (1) Developing multiscale theoretical models to study ice formation, including validated potentials for water, interactions at interfaces, and effects of additives and anti-icing agents; (2) Performing experimental studies to probe the dynamics of liquid water as it nucleates, and the interaction of interfaces and anti-icing agents with critical size clusters or nanocrystals that would, in their absence, lead to bulk ice formation; (3) Elucidating structure-antifreeze activity relationships, and validating theoretical models against benchmark experimental data; (4) Rationally designing biomimetic peptides, organic surfaces, or related materials that will provide antifreeze activity.

Anticipated Resources: It is anticipated that awards under this topic will be no more than an average of $1.5M per year for 5 years, supporting no more than 8 funded faculty researchers. Exceptions warranted by specific proposal approaches should be discussed with the topic chief during the white paper phase of the solicitation.

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