BROAD AGENCY ANNOUNCEMENT (BAA)

INTRODUCTION:

This publication constitutes a Broad Agency Announcement (BAA) as contemplated in Department of Defense Grant and Agreement Regulation (DODGARS) 22.315(a). A formal Request for Proposals (RFP), solicitation, and/or additional information regarding this announcement will not be issued. Request for same will be disregarded.

The Office of Naval Research (ONR) will not issue paper copies of this announcement. The ONR and Department of Defense (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 ONR and other participating 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 BAA will not be returned. It is the policy of ONR and participating DoD agencies to treat all proposals as sensitive competitive information and to disclose their contents only for the purposes of evaluation.

The DoD Multidisciplinary University Research Initiative (MURI), one element of the University Research Initiative (URI), is sponsored by the DoD research offices: 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").

Awards will take the form of grants. Therefore, proposals submitted as a result of this announcement will fall under the purview of the Department of Defense Grant and Agreement Regulations (DoDGARs).

Potential offerors may obtain information on ONR programs and opportunities by checking the ONR website at http://www.onr.navy.mil/en/Contracts-Grants/Funding-Opportunities/Broad-Agency-Announcements.aspx.

I. GENERAL INFORMATION

1. Agency Name

Office of Naval Research
875 North Randolph Street - Suite 1425
Code 03R
Arlington, VA 22203-1995

2. Research Opportunity Title

Multidisciplinary University Research Initiative (MURI)

3. Program Name

Fiscal Year (FY) 2012 Department of Defense Multidisciplinary Research Program of the University Research Initiative

4. Research Opportunity Number

BAA 11-26

5. Response Date

White Papers: Thursday, 15 September 2011

Full Proposals: Thursday, 10 November 2011

6. Research Opportunity Description

Synopsis

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 interact to provide rapid advances in scientific areas of interest to the DoD. As defined by the DoD, "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." (http://comptroller.defense.gov/fmr/02b/02b_05.pdf). The DoD's basic research program invests broadly in many specific fields to ensure that it has early cognizance of new scientific knowledge.

The FY 2012 MURI competition is for the topics listed below. Detailed descriptions of the topics can be found in Section VIII entitled, "Specific MURI Topics", of this BAA. The detailed descriptions are intended to provide the proposer 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.

White papers and full proposals addressing the following topics (1) through (8) should be submitted to the Army Research Office (ARO):

(1) Quantized Chemical Reactions of Ultracold Molecules
(2) 3D Topological Insulators with Interactions
(3) Translating Biochemical Pathways to Non-Cellular Environments
(4) Multivariate Heavy-Tailed Statistics: Foundations and Modeling
(5) Simultaneous Multi-Synaptic Imaging of the Interneuron
(6) Revolutionizing High-Dimensional Microbial Data Integration
(7) Novel Nanostructures for the Controlled Propagation of Electromagnetic Energy
(8) Predictive Models of Cultural and Behavioral Effects on Societal Stability

White papers and Full proposals addressing the following topics (9) through (14) should be submitted to the Air Force Office of Scientific Research (AFOSR):

(9) Directional Eutectic Structures: Self-Assembly for Metamaterials and Photonics
(10) Smart, Functional Nanoenergetics Design from the Atomistic/Molecular Scale through the Mesoscale
(11) Managing Informational Complexity in Predictive Materials Science
(12) Deep Atmospheric Optical Turbulence Physics and Predictive Modeling
(13) Quantum Metaphotonics/Metamaterials
(14) High Power, Low-Loss, Artificial Materials for Transformational Electromagnetics

White papers and full proposals addressing the following topics (15) through (21) should be submitted to The Office of Naval Research:

(15) Morphable Dynamic Information Processing
(16) Extended-Range Environmental Prediction Using Low-Dimensional Dynamic Modes
(17) A New Way to Dissipate Shock Wave Energy from Detonations
(18) Programming Biology to Attain Non-Natural Functions
(19) Predicting the Behavior of Complex, Non-Deterministic Autonomous Systems and Mixed Autonomous/Manned Teams under Realistic Assumptions
(20) Extreme Electron Concentration Materials and Devices
(21) Super-hydrophobic Surface for Skin Friction Drag Reduction in High Reynolds Number Turbulent Flow

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.

7. Point(s) of Contact

One or more Research Topic Chiefs are identified for each specific MURI Topic. Questions of a technical nature shall be directed to one of the Research Topic Chiefs identified in Section VIII entitled, "Specific MURI Topics" of this BAA.

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. Bill Lukens MURI Program Manager
Office of Naval Research, Code 03R
E-mail Address: william.lukens1@navy.mil

Mailing address:
Office of Naval Research
One Liberty Center
875 North Randolph Street, Suite 1409
Arlington, VA 22203-1995

Questions of a *business nature* for all three (3) services shall be directed to the cognizant Contract Specialist, as specified below:

Primary:
Jennifer Brown
Contract and Grants Awards Management, Code ONR 0251
Office of Naval Research
875 North Randolph Street, Suite W1273
Arlington, VA 22203-1995
E-Mail: jennifer.williams4@navy.mil

Secondary:
Vera M. Carroll
Acquisition Branch Head
Contract and Grants Awards Management, Code 0251
Office of Naval Research
875 North Randolph Street, Suite 1279
Arlington VA, 22203-1995
E-mail: vera.carroll@navy.mil

Questions submitted within 2 weeks prior to a deadline may not be answered, and the due date for submission of the white paper and/or full proposal will not be extended.

Answers to questions submitted in response to this BAA will be addressed in the form of an Amendment and will be posted to one or more of the following webpages:

- Grants.gov Webpage – http://www.grants.gov/
- ONR Broad Agency Announcement (BAA) Webpage – http://www.onr.navy.mil/en/Contracts-Grants/Funding-Opportunities/Broad-Agency-Announcements.aspx

8. Instrument Type(s)

It is anticipated that all awards resulting from this announcement will be grants.

9. Catalog of Federal Domestic Assistance (CFDA) Numbers

12.300 ONR
12.800 AFOSR
12.431 ARO

10. Catalog of Federal Domestic Assistance (CFDA) Titles

Basic and Applied Scientific Research, (ONR)
Air Force Defense Research Sciences Program, (AFOSR)
Basic Scientific Research, (ARO)

11. Other Information

11. Other Information –

The Non-ONR Agency Information:

Air Force Office of Scientific Research
875 North Randolph Street
Suite 325 Room 3112
Arlington, VA 22203-1768

Army Research Office
4300 S. Miami Blvd.
Durham, NC 27703-9142

Work funded under this BAA must be fundamental research. With regard to any restrictions on the conduct or outcome of work funded under this BAA, ONR will follow the guidance on and definition of "contracted fundamental research" as provided in the Under Secretary of Defense (Acquisition, Technology and Logistics) Memorandum of 24 May 2010.

As defined therein the definition of "contracted fundamental research," in a DoD contractual context, includes [research performed under] grants and contracts that are (a) funded by Research, Development, Test and Evaluation Budget Category 1 (Basic Research), whether performed by universities or industry or (b) funded by Budget Category 2 (Applied Research) and performed on campus at a university. The research shall not be considered fundamental in those rare and exceptional circumstances where the applied research effort presents a high likelihood of disclosing performance characteristics of military systems or manufacturing technologies that are unique and critical to defense, and where agreement on restrictions have been recorded in the contract or grant.

Pursuant to DoD policy, research performed under grants and contracts that are a) funded by Budget Category 6.2 (Applied Research) and NOT performed on-campus at a university or b) funded by Budget Category 6.3 (Advanced Research) does not meet the definition of "contracted fundamental research." In conformance with the USD (AT&L) guidance and National Security Decision Direction 189, ONR will place no restriction on the conduct or reporting of unclassified "contracted fundamental research," except as otherwise required by statute, regulation or Executive Order. For certain research projects, it may be possible that although the research being performed by the prime contractor is restricted research, a subcontractor may be conducting "contracted fundamental research." In those cases, it is the ***prime contractor's responsibility*** in the proposal to identify and describe the subcontracted unclassified research and include a statement confirming that the work has been scoped, negotiated, and determined to be fundamental research according to the prime contractor and research performer.

Normally, fundamental research is awarded under grants with universities and under contracts with industry. Non-fundamental research is normally awarded under contracts and may require restrictions during the conduct of the research and DoD pre-publication review of such research results due to subject matter sensitivity.

II. AWARD INFORMATION

It is anticipated the awards will be made in the form of grants 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 2-year option period to bring the total maximum term of the award to five years. The base and option period will be incrementally funded.

Total amount of funding for five years available for grants resulting from this MURI BAA is estimated to be about $250 million dollars pending out-year appropriations. MURI awards are $1M- $1.5M per year, with the actual amount contingent on availability of funds, the specific topic, and the scope of the proposed work. With few exceptions an individual award may not exceed $1.5M per year. It is strongly recommended that potential proposers communicate with the Program Topic Chief 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.**

III. ELIGIBILITY INFORMATION

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

When a modest amount of additional funding for an ineligible organization is necessary to make the proposed collaboration possible, such funds may be requested via a separate proposal from that organization. This supplemental proposal should be attached to the primary MURI proposal and will be evaluated separately by the responsible Research Topic Chief. If approved, the supplemental proposal will be funded by the responsible agency using non-MURI funds. Since it is not certain that non-MURI funding would be available for ineligible organizations, Principal Investigators are encouraged to restrict funding requests to eligible organizations when practical.

Awards under this BAA will be made only to U.S. Institutions of Higher Education which award degrees in science and/or engineering. Historically Black Colleges and Universities (HBCUs) and Minority Institutions (MIs) are encouraged to submit proposals and join others in submitting proposals. However, no portion of this BAA will be set aside for HBCU and MI participation.

The Federal Funding Accountability and Transparency Act of 2006 (Public Law 109-282), as amended by Section 6202 of Public Law 110-252, requires that all agencies establish requirements for recipients reporting information on subawards and executive total compensation as codified in 2 CFR 170.110. Any company, non-profit agency or university that applies for financial assistance (either grants, cooperative agreements or other transaction agreements) as either a prime or sub-recipient under this BAA 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 170.220. An entity is **exempt** from this requirement **UNLESS** in the preceding fiscal year it received: a) 80 percent or more of its annual gross revenue in Federal contracts (and subcontracts), loans, grants (and subgrants), and cooperative agreements; b) $25 million or more in annual gross revenue from Federal contracts (and subcontracts), loans, grants (and subgrants), and cooperative agreements; and c) the public does not have access to information about the compensation of the senior executives through periodic reports filed under section 13(a) or 15(d) of the Securities Exchange Act of 1934 or section 6104 of the Internal Revenue Code of 1986.

IV. APPLICATION AND SUBMISSION INFORMATION

1. Application and Submission Process

The proposal submission process is in two stages. Prospective awardees are encouraged to submit white papers to minimize the labor and cost associated with the production of detailed full 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 them to submit full proposals. The Topic Chief may also on occasion provide feedback encouraging reteaming to strengthen a proposal.

White papers arriving after the deadline may not receive feedback prior to full proposal submission. However, all full proposals submitted under the terms and conditions cited in the BAA will be reviewed.

Due Date: The due date for white papers is no later than 4:00 P.M. (Eastern Time) on Thursday, 15 September 2011.

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), via a commercial carrier at the agency specified for the topic. For hard copy submissions, use the addresses provided in Section IV entitled, "Application and Submission Information" paragraph number 6 entitled, "Address for the 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.

Evaluation/Notification: Initial evaluations of the white papers will be issued on or about Thursday, 29 September 2011.

Submission of Full Proposal:

Any Offeror may submit a full proposal even if its white paper was not identified as being of "particular value" to the Government. However, the initial evaluation of the white papers should give prospective awardee some indication of whether a later full proposal would likely result in an award.

NOTE: Full Proposals must be submitted electronically through grants.gov.

Registration Requirements for Grants.gov: There are several one-time actions you must complete in order to submit an application through Grants.gov (e.g., obtain a Dun and Bradstreet Data Universal Numbering System (DUNS) number, register with the Central Contract Registry (CCR), register with the credential provider, and register with Grants.gov). See www.grants.gov/GetStarted to begin this process. Use the Grants.gov Organization Registration Checklist at www.grants.gov/assets/OrganizationRegCheck.doc to guide you through the process. Designating an E-Business Point of Contact (EBiz POC) and obtaining a special password called an MPIN are important steps in the CCR registration process. Applicants, who are not registered with CCR and Grants.gov, should allow at least 21 days completing these requirements. It is suggested that the process be started as soon as possible.

Questions: Questions relating to the registration process, system requirements, how an application form works, or the submittal process must be directed to Grants.gov at 1-800-518-4726 or support@grants.gov.

2. Content and Format of White Papers and Full Proposals

The white papers and full proposals submitted under this BAA are expected to address unclassified basic research. White papers and full proposal submissions will be protected from unauthorized disclosure in accordance with applicable law and DoD regulations. Proposers are expected to appropriately mark each page of their submission that contains proprietary information. Grants awarded under this announcement shall be unclassified.

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

a. White Paper Submission: Contents and Format of Applications

Each topic in this announcement has one or more Research Topic Chiefs identified from one of the participating agencies; ONR, AFOSR, or ARO. You should submit your white paper to one of the Research Topic Chiefs at the agency for which you are applying.

White paper 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
- Number of Pages - no more than four (4) single-sided pages (excluding cover letter, cover, and curriculum vitae). White papers exceeding the page limit may not be evaluated.

White Paper content should be as follows:

- A one page cover letter (optional)
- A cover page, labeled "PROPOSAL WHITE PAPER," that includes the BAA 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

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.

Copies – one (1) original and two (2) copies.

b. Grants.gov Full Proposal Submission: Content and Format of Applications

Application forms and instructions are available at Grants.gov. To access these materials, go to http://www.grants.gov, select "Apply for Grants", and then select "Download Application Package". Enter the CFDA for the respective agency to which you are directing the application (ONR – 12.300, AFOSR – 12.800, ARO – 12.431), as found on page five of this announcement) and the funding opportunity number, designated as "research opportunity number" on page two of this announcement. Each topic in this announcement has a Research Topic Chief identified from one of the participating agencies; ONR, AFOSR, or ARO. You should direct your application to the agency associated with the topic for which you are applying.

Content and Form of Application – SF 424 (R&R) - Mandatory

You must complete the mandatory forms in accordance with the instructions 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.**

Form: SF 424 (R&R) - Mandatory

Complete this form first to populate data in other forms. Complete all the required fields in accordance with the pop-up instructions on the form. To activate the instructions, turn on the "Help Mode" (icon with the pointer and question mark at the top of the form). To be considered for award, applicants must fill out block 4 of the SF 424 R&R as follows: Block 4a "Federal Identifier": leave blank; Block 4b "Agency Routing Identifier": enter the appropriate topic chief's name.

Form Research & Related Other Project Information - Mandatory

Complete questions 1 through 6 and attach files. The files must comply with the following instructions:

Project Summary/Abstract (Field 7 on the Form) - Mandatory

The project summary should be a single page that identifies the research problem, technical approaches, anticipated outcome of the research, if successful, and impact on DoD capabilities. It should identify the Principal Investigator, the university and other universities involved in the MURI team if any, the proposal title, the agency to which the proposal is submitted, the MURI topic number and the total funds requested from DoD for the 3-year base period, the 2-year option period and the 5-year total period. The project summary must not exceed 1 page when printed using standard 8.5" by 11" paper with 1" margins (top, bottom, left and right) with font Times New Roman 12 point. To attach a Project Summary/Abstract, click "Add Attachment."

Project Narrative (Field 8 on the form) - Mandatory

<u>The Following Formatting Rules Apply for Field 8</u>

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

<u>Include the Following in Field 8</u>

The first page of your narrative must include the following information:

- Principal Investigator name

- Phone number, fax number and e-mail address
- Institution, Department, Division
- Institution address
- Other universities involved in the MURI team
- 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 full time equivalent graduate students and undergraduates, if any, to be supported each year. Discuss the involvement of other students, if any.

- Project Schedule, Milestones and Deliverables: A summary of the schedule of events, milestones, and a detailed description of the results and products to be delivered.

- 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.

  (a) 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, by version and/or configuration that are required for the proposed effort.

  (b) 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.

  (c) 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 Program Topic Chief. Briefly summarize the qualifications of the Principal Investigator and other key investigators to conduct the proposed research.

  (d) List the amount of funding and describe the research activities of the Principal Investigator and co-investigators in on-going and pending research projects, whether or not acting as Principal Investigator in these other projects, the time charged to each of these projects, and their relationship to the proposed effort.

(e) Describe plans to manage the interactions among members of the proposed research team.

(f) 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 three Letters of Support from various DoD agencies may be included.
- Curriculum Vitae: Include curriculum vitae of the Principal Investigator and key co-investigators.

All applications should be in a single PDF file. To attach a Project Narrative in Field 8, click "Add Attachment."

Bibliography & References Cited (Field 9 on the form)

This field not required.

Facilities & Other Resources (Field 10 on the form)

This field not required.

Equipment (Field 11 on the form)

This field not required.

Other Attachment (Field 12 on the form)

Attach budget proposal at field 12. You must provide a detailed cost breakdown of all costs, by cost category and by the funding periods described below, corresponding to the proposed Technical Approach which was provided in Field 8 of the Research and Related Other Project Information Form. The option must be separately priced. The Research and Related Budget form is not required.

The budget should adhere to the following guidelines:

Detailed breakdown of all costs, by cost category, by the calendar periods stated below. For budget purposes, use an award start date of 01 June 2012. For the three-year base grant, the cost should be broken down to reflect funding increment periods of:

(1) Four months (01 Jun 12 to 30 Sep 12),
(2) Twelve months (01 Oct 12 to 30 Sep 13),
(3) Twelve months (01 Oct 13 to 30 Sep 14), and
(4) Eight months (01 Oct 14 to 31 May 15).

Note that the budget for each of the calendar periods (e.g. 01 June 12 to 30 Sep 12) should

include only those costs to be expended during that calendar period.
The budget should also include an option for two additional years broken down to the following funding periods:

(1) Four months (01 Jun 15 to 30 Sep 15),
(2) Twelve months (01 Oct 15 to 30 Sep 16), and
(3) Eight months (01 Oct 16 to 31 May 17).

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 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 (i.e., 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 – Provide a description of the work to be performed by the subrecipients. For each subaward, a detailed cost proposal is required to be included in the principal investigator's cost proposal. Fee/profit is unallowable.
• 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 contractor's proposal.
• Materials & Supplies – Provide an itemized list of all proposed materials and supplies including quantities, unit prices, proposed vendors (if known), 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, office equipment and furnishings, etc.) 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 other 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).
NOTE: If the grant proposal is for a conference, workshop, or symposium, the proposal should include the following statement: "The funds provided by ONR will not be used for food or beverages."
• Fee/Profit – Fee/profit is unallowable.

Funding Breakdown

Funding breakdown corresponding to the proposed Technical Approach which was provided in Field 8 of the Research and Related Other Project Information Form must also be attached.

Proposal Receipt Notices

After a full proposal is submitted through Grants.gov, the Authorized Organization Representative (AOR) will receive a series of three e-mails. It is extremely important that the AOR watch for and save each of the e-mails. You will know that your proposal has reached ONR, ARO or AFOSR when the AOR receives e-mail Number 3. You will need the Submission Receipt Number (e-mail Number 1) to track a submission. The three e-mails are:

Number 1 – The applicant will receive a confirmation page upon completing the submission to Grants.gov.

Number 2 – The applicant will receive an e-mail 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.)

Number 3 – The third notice is an acknowledgment of receipt in e-mail form from the designated agency within ten days from the proposal due date. The e-mail is sent to the authorized representative for the institution. The e-mail for proposals notes that the proposal has been received and provides the assigned tracking number.

3. Significant Dates and Times

Schedule of Events		
Event	**Date**	**Time**
Questions Regarding **white papers**	01 September 2011*	2:00PM Eastern Daylight Time
White Papers Due	15 September 2011	4:00 PM Eastern Daylight Time
Notification of Initial DoD Evaluations of White Papers	29 September 2011**	
Questions Regarding **full proposals**	27 October*	2:00PM Eastern Daylight Time
Full Proposals Due	10 November 2011	4:00 PM Eastern Daylight Time
Notification of Selection for Award	10 March 2012**	
Start Date of Grant	01 June 2012*	

*Questions received after this date and time may not be answered, and the due date for submission of the proposals 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 the Office of Naval Research has increased. Materials submitted through the U.S. Postal Service, for example, may take seven days or more to be received, even when sent by Express Mail. Thus, any hard-copy proposal should be submitted long enough before the deadline established in the solicitation so that it will not be received late and thus be ineligible for award consideration.

4. Submission of Late Proposals

Any full proposal submitted and validated through Grants.gov where the time and date for submission (e-mail Number #2) is after the deadline for proposal submission in Section IV entitled, "Application and Submission Information" paragraph number 3 entitled, "Significant Dates and Times" will be late and will not be evaluated unless the Grants.gov website was not operational on the due date and was unable to receive the proposal submission. If this occurs, the time specified for the receipt of proposals through Grants.gov will be extended to the same time of the day specified in this BAA on the first workday on which the Grants.gov website is operational.

Be advised that Grants.gov applicants have been experiencing system slowness and validation issues which may impact the time required submitting proposals. After proposals are uploaded to grants.gov, the submitter receives an email indicating the proposal has been submitted and that grants.gov will take up to two days to validate the proposal. As it is possible for grants.gov to reject the proposal during this process, it is STRONGLY recommended that any soft-copy proposals be uploaded at least two days before the deadline established in the solicitation so that it will not be received late and be ineligible for award consideration.

a. For ARO, use the following alternative to submitting proposals to grants.gov.

Email your completed proposal package and grants.gov trouble ticket/case number to aror.baa@us.army.mil. Your proposal must include all signatures and attachments and be submitted in PDF format. All proposal submissions will be subsequently evaluated by ARO for completeness and an official email confirmation will be sent. Incomplete packages will not be considered for an award. All submissions must meet the deadline specified in the BAA

b. For AFOSR submissions please email your completed proposal package and grants.gov trouble ticket/case number to proposal@afosr.af.mil. Each email may not exceed 35MB. If necessary, use multiple emails sending the full proposal noting the trouble ticket/case number. Your proposal must include all signatures and attachments and be submitted in PDF format. An auto-reply email will be returned to the sender indicating that your email arrived. All proposal submissions will be subsequently evaluated by AFOSR for completeness and an official email confirmation will be sent. Incomplete packages will not be considered for an award. All submissions must meet the deadline of 4:00 (Eastern Time) 10 November 2011.

c. There is no alternative process for ONR. Full proposals must be submitted through grants.gov

5. Address for Submission of Hard Copy White Papers

Submission of white papers shall be sent to the addresses below:

Important Notes Regarding Submission of Hard Copy White Papers:

If the Offeror 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.

U.S. Army Research Office:

Hard copy white papers addressing topics (1) to (8) should be sent to the U.S. Army Research Office at one of the following addresses:

For delivery by USPS (ordinary First Class or Priority Mail (but not Express Mail)):

U.S. Army Research Office (FY12 MURI)
P. O. Box 12211
Research Triangle Park, NC 27709-2211

For commercial delivery (such as Express Mail, FedEx, UPS, etc.):

U.S. Army Research Office (FY12 MURI)
For white papers include: ATTN: (list name of responsible Research Topic Chief)
4300 S. Miami Blvd
Durham, NC 27703-9142
919-549-4211

Air Force Office of Scientific Research:

Hard copy white papers addressing topics (9) to (14) 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

Office of Naval Research:

Hard copies of white papers topics (15) to (21) 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 1409*
Arlington, VA 22203-1995
Point of Contact: Dr. William Lukens
Email: William.lukens1@navy.mil
703-696-4668

*This is the address for hand delivery, delivery via USPS and delivery via commercial delivery services.

If a telephone number is required, please use 703-696-4111 or 703-696-4668.

NOTE: White Papers sent by fax or hand delivered will not be considered.

V. EVALUATION INFORMATION

1. Evaluation Criteria

A. Basic Research: The MURI Program is funded by basic research (Budget Activity 1) money. White papers and full 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 requirements." The full definitions of these terms are contained in the links http://comptroller.defense.gov/fmr/02b/02b_05.pdf

White papers will be evaluated by the responsible Research Topic Chief 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 full proposal. The assessment will focus on scientific and technical merits (criterion 1, below), potential for the research to significantly advance fundamental understanding in the topic area (criterion 2 below), and potential DoD interest (criterion 3, below), although the other criteria may also be used in making the assessment.

Full proposals responding to this BAA in each topic area will be evaluated using the following criteria. The first four evaluation factors are of equal importance:

(1) Scientific and technical merits of the proposed basic science and/or engineering research;

(2) Potential for the research, if successful, to significantly advance fundamental understanding in the topic area;

(3) DoD potential interest in the proposed research; and

(4) qualifications and availability of the Principal Investigator and key co-investigators.

The following three evaluation criteria are each of lesser importance than any of the above four, but are equal to each other:

(5) adequacy of current or planned facilities and equipment to accomplish the research objectives;

(6) 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

(7) realism and reasonableness of cost (cost sharing is not a factor in the evaluation).

Decisions for exercising options will be based on accomplishments during the base years and potential research advances during the option years that can impact DoD research priorities and technological capabilities.

2. Evaluation Panel

White papers 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 specialized government employees secured under the Intergovernmental Personnel Act (IPA). These individuals will sign a conflict of interest statement prior to receiving proposal information.

Full proposals will undergo a multi-stage evaluation procedure. The cognizant Program Officer 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 peers from the university community may be utilized as subject-matter-expert technical consultants. Similarly, support contractors may be utilized to evaluate cost proposals. However, proposal selection and award decisions are solely the responsibility of Government personnel. Each support contractor's employee and peer from the university community having access to technical and cost proposals submitted in response to this BAA will be required to sign a non-disclosure 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 by the Principal Investigator and the government prior to final award.

VI. AWARD ADMINISTRATION INFORMATION

1. Administrative Requirements –

Central Contractor Registration: All Offerors submitting proposals or applications must:

(a) be registered in the Central Contractor Registration (CCR) prior to submission;
(b) maintain an active CCR 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.

2. Reporting

In general, for each grant award, annual reports and a final report are required summarizing the technical progress and accomplishments during the performance period, as well as any other report as requested by the Research Topic Chief.

VII. OTHER INFORMATION

1. Government Property/Government Furnished Equipment (GFE) and Facilities

Government research facilities and operational military units are available and should be considered as potential government-furnished equipment/facilities. These facilities and resources are of high value and some are in constant demand by multiple programs. It is unlikely that all facilities would be used for any one specific program. The use of these facilities and resources will be negotiated as the program unfolds. Offerors should explain as part of their proposals which of these facilities are critical for the project's success.

2. Use of Animals and Human Subjects in Research

If animals are to be utilized in the research effort proposed, the Offeror must complete a DoD Animal Use Protocol with supporting documentation (copies of AAALAC accreditation and/or NIH assurance, IACUC approval, research literature database searches, and the two most recent USDA inspection reports) prior to award. For assistance with submission of animal research related documents, contact the ONR Animal Use Administrator at (703) 696-4046.

Similarly, for any proposal for research involving human subjects, the Offeror must submit or indicate an intention to submit prior to award: documentation of approval from an Institutional Review Board (IRB); IRB-approved research protocol; IRB-approved informed consent form; proof of completed human research training (e.g., training certificate or institutional verification of training); an application for a DoD-Navy Addendum to the Offeror's DHHS-issued Federal wide Assurance (FWA) or the Offeror's DoD-Navy Addendum. In the event that an exemption criterion under 32 CFR.219.101 (b) is claimed, provide documentation of the determination by the Institutional Review Board (IRB) Chair, IRB vice Chair, designated IRB administrator or official of the human research protection program including the category of exemption and short rationale statement. This documentation must be submitted to the ONR Human Research Protection Official (HRPO), by way of the ONR Program Officer. Information about assurance applications and forms can be obtained by contacting ONR_343_contact@navy.mil. If the research is determined by the IRB to be greater than minimal risk, the Offeror also must provide the name and contact information for the independent medical monitor. For assistance with submission of human subject research related documentation, contact the ONR Human Research Protection Official at (703) 696-4046.

For contracts and orders, the award and execution of the contract, order, or modification to an existing contract or order serves as notification from the Contracting Officer to the Contractor that the HRPO has approved the assurance as appropriate for the research under the Statement of Work and also that the HRPO has reviewed the protocol and accepted the IRB approval or exemption determination for compliance with the DoD Component policies. See, DFARS 252.235-7004.

3. Recombinant DNA

Proposals which call for experiments using recombinant DNA must include documentation of compliance with Department of Human and Health Services (DHHS) recombinant DNA regulations, approval of the Institutional Biosafety Committee (IBC), and copies of the DHHS Approval of the IBC letter.

4. Department of Defense High Performance Computing Program

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

5. Project Meetings and Reviews

Individual program reviews between the sponsor 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 be held at various sites throughout the country. For costing purposes, offerors should assume that 40% of these meetings will be at or near ONR, Arlington, VA and 60% at other contractor or government facilities. Interim meetings are likely, but these will be accomplished via video telephone conferences, telephone conferences, or via web-based collaboration tools.

6. Other Guidance, Instructions and Information

None

VIII. SPECIFIC MURI TOPICS

ARO FY2012 MURI TOPIC #1

Submit white papers and proposals to the Army Research Office

Quantized Chemical Reactions of Ultracold Molecules

Background: Ultracold molecular reactions, where chemical reactions take place in the sub-millikelvin temperature regime, is a new field of scientific study. In the paper by Ye, *et. al.* (*Science* 2010, 327, 853-857) molecules of KRb formed at nano-kelvin temperatures and researchers measured their subsequent bi-molecular reaction rates, forming K2 and Rb2. Nano-kelvin chemical reactions are radically different than those that occur at "normal" temperatures. Molecular ensembles are no longer described by a Boltzmann energy distribution. Instead, a fully quantum description including spin statistics of the atomic species is required to describe the reactions. Moreover, ultracold molecules can react even at intermolecular separations of micrometers, and under conditions where the collision energy approaches zero. The reactions become heavily dependent on nuclear spin orientation, interaction strength, and correlations. These features make them a robust testbed for long range interacting many body systems, controlled reactions and precision measurements. Along with recent demonstrations in ultracold quantum molecular reactivity, another leading-edge experiment demonstrates a new cooling technique for diatomic molecules. DeMille *et al. (Nature* 2010, 467, 820-823) showed the ability to laser cool an entire class of diatomic molecules. Previously, it was believed that the large number of rovibrational states inherent in molecules made a closed cycling transition impractical, a requirement for laser cooling. However, DeMille et al. was able to implement a scheme that prevented the molecules from spontaneously relaxing into dark states and was then able to cool the molecules into the hundreds of microkelvin temperature range with only three lasers required. These two scientific accomplishments open a new domain for the study of quantum reactive processes in the nanokelvin regime. This new and exciting area of research is strategically positioned to advance the fields of ultracold atomic and molecular gases as well as quantum chemistry.

Objective: The objectives of this MURI are to develop a fundamental understanding of the nature of molecular reactions in the nanokelvin temperature regime and to extend the cooling technique of DeMille *et al.* to other molecular candidates. Specific focus will be on the implementation of novel and efficient laser cooling techniques of diatomic molecules and to understand the role of quantum effects, including the role of confined geometries, on molecules that possess vanishingly small amounts of thermal energy.

Research Concentration Areas: Suggested research areas may include, but are not limited to the following: 1.) Extend known laser cooling methods for atoms and alkaline earth/halogen diatomic molecules to other classes of diatomic molecules; 2.) Direct chemical reactions for atom-molecule reactions and molecule-molecule reactions in the nanokelvin temperature regime and determine the role of quantum effects and constrained geometries in these reactions; 3.) Explore novel quantum chemistry to develop products either not available in the classical limit, or to substantially change the product ratios using quantum controlled reactions; and, 4.) Develop new, non-statistical theories of chemical reactivity to explain the experimental observations and provide insight into as yet unknown phenomena which govern such molecular processes in the nanokelvin regime.

Research Topic Chiefs:
Dr. James Parker, ARO, (919) 549-4293, james.kenneth.parker@us.army.mil
Dr. Paul Baker, ARO, (919) 549-4202, paul.m.baker1@us.army.mil

ARO FY2012 MURI TOPIC #2

Submit white papers and proposals to the Office of Army Research

3D Topological Insulators with Interactions

Background: The quantum Hall (QH) state was the first quantum state of matter discovered to not be characterized by a broken symmetry but rather by a quantized topological invariant. Since then, topological invariants have been found to have roles in superconducting, metallic and insulating materials. Topological invariants in this last system – insulators – are a recent discovery shown to have fantastic consequences. Strong spin-orbit coupling in certain insulators will invert the electronic structure from its usual ordering. This combined with the fundamental nature of electrons results in what is referred to as a non-trivial Z2 time-reversal invariant topological insulator. In two dimensions, the result is a quantum spin Hall (QSH) state which mimics the QH state yet without a magnetic field. In three dimensions, a topological insulator has a topologically protected metallic surface when adjacent to a normal insulator. Unlike a metal, these surfaces states are non-degenerate in spin and electrons with opposite momentum have opposite spin. Advances in materials with significant spin-orbit coupling have led to strong evidence for these states from photoemission and, in 2010 and 2011, transport studies. With further advances, the field is poised to explode with discoveries of new phenomena in physics and electronics. Theory has predicted that these materials will exhibit a non-trivial coupling between electric and magnetic fields allowing electric field control of magnetization. Because the change in magnetization is the result of orbital effects rather than ion motion, the materials should be immune to the ion-motion induced fatigue. Furthermore, theory anticipates the presence of quasi-particles with fractional quantum statistics – those not conforming to either Bose or Fermi statistics. The latest experimental studies appear to corroborate this prediction. Theories of topological insulators are only beginning to include interactions. Accordingly, a predominant theme of the 'next frontier' of topological insulators involves (i) the effect of interactions on topological insulator phenomena and (ii) the competition of topological and conventional orders. Here progress will be enabled by further advances in solid-state chemistry, materials science, unique spectroscopies and transport studies, and many-body theories.

Objective: The goal of this topic is to study experimentally and understand theoretically topological insulators that (i) involve interactions, (ii) are of classes beyond the Z2 time reversal invariant class, and (iii) compete with conventional phases either directly or through the proximity effect.

Research Concentration Areas: Areas of interest include, but are not limited to, the following: (1) Experimental approaches in solid state chemistry and materials science to further enhance the bulk resistivity and surface electron mobility of known 3D topological insulators and to explore new topological insulators including doping, unique materials, and the combination of competing conventional orders with topological orders. (2) Surface science for the investigation of local bonding, physical and electronic structure, and growth modes of topological insulators and other materials, which influence the physics of the topologically protected states. (3) Characterization to verify the phenomena and experimentally validate theoretical propositions. (4) Phenomenological and/or *ab initio* theoretical studies to develop an understanding of how interactions modify the topological insulator phenomena or give rise to new phases.

Research Topic Chief:
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Dr. Pani Varanasi, ARO, (919) 549-4325, pani.varanasi@us.army.mil

ARO FY2012 MURI TOPIC #3

Submit white papers and proposals to the Office of Army Research

Translating Biochemical Pathways to Non-Cellular Environments

Background: Cells provide a precisely organized environment to promote maximum efficiency of biochemical reaction pathways, with individual enzymatic components organized via multi-subunit complexes, targeted localization in membranes, or specific interactions with scaffold proteins. The eventual translation of these complex pathways to engineered systems will require the ability to control and organize the individual components outside of the natural cellular environment. Biological molecules have been attached directly to inorganic materials; however this often requires chemical modification of the molecule and can restrict its conformational freedom. An alternative approach to maintain biological activity outside of the cell, while preserving conformational freedom, is to encapsulate enzymes within specialized materials or structures. However, surface patterning of current encapsulating agents has not achieved the precision required to replicate the organizational capabilities of the cell. Several recent scientific developments support the exploration of 3D DNA nanostructures as encapsulating agents that could also achieve spatial organization of pathway components within inorganic materials. Computational design capabilities now support the rational design of 3D DNA nanostructures that could accommodate dynamic enzymes. Moreover, recent advances in experimental visualization and physical/structural characterization of biomolecular assemblies (e.g., high-speed atomic force microscopy, cryo-electron microscopy) have provided increased temporal and spatial resolution, enabling enhanced precision and real-time kinetic analyses. Recent work has also demonstrated the successful arrangement of DNA origami on the surface of lithographically-patterned materials according to physical shape and size.

Objective: The objective of this MURI is to develop the scientific foundations needed to design, assemble, and analyze a natural or synthetic biochemical pathway (e.g., photosystem II) translated to a non-cellular environment using three-dimensional DNA nanostructures to provide both a surrogate environment that promotes biological activity and a means to organize the individual pathway components on an inorganic surface.

Research Concentration Areas: Suggested research areas include, but are not limited to: 1) Develop computational methods to design three-dimensional DNA structures that accommodate enzymatic conformational changes and allow access to substrate and release of product. 2) Design strategies for promoting efficient enzymatic activity via chemical modification of DNA nanostructures. 3) Develop methods to confine DNA nanostructures on inorganic surfaces, with control over relative spacing and orientation. 4) Devise strategies for surface arrangement of the biochemical pathway that maximize the efficiency of the reaction and that will translate to more complex porous materials. 5) Characterize the activity of the non-cellular biochemical pathway as a function of the surrogate environment provided by the DNA nanostructures and as a function of the surface arrangement of the pathway components.

Research Topic Chiefs:
Dr. Stephanie McElhinny, ARO, (919) 549-4240, stephanie.mcelhinny@us.army.mil
Dr. John Prater, ARO, (919) 549-4259, john.t.prater@us.army.mil.

ARO FY2012 MURI TOPIC #4

Submit white papers and proposals to the Army Research Office

Multivariate Heavy-Tailed Statistics: Foundations and Modeling

Background: Over the past three decades, phenomena in a large and increasing number of areas such as communication, networks (including social), geometric modeling, information fusion, face/pattern recognition, cyber security, risk analysis, extreme-event analysis, finance, economics, insurance, and criminology, have been shown to follow heavy-tailed statistical distributions. These are distributions with many outliers and tails that decrease as sub-exponential functions. The heavy-tailed-distributed nature of Internet traffic was discovered in 1993. Characteristics of heavy-tailed-distributed data include long-range dependence. Analysis for phenomena that follow heavy-tailed distributions is much more challenging than analysis for classical "light-tailed" distributions (Gaussian, Poisson,etc.), which have tails that decrease exponentially. Virtually all of the known analytical results about heavy-tailed distributions are for univariate distributions. While there have been attempts in the past decade to define and characterize multivariate heavy-tailed distributions, basic forms and principles of such distributions are still poorly known. As a result, multivariate Gaussian assumptions continue to dominate in system modeling and systems are built that are inconsistent with empirical observations. The common practice of "approximately modeling" heavy-tailed distributed phenomena using light-tailed (e.g., Gaussian) distributions is often not even approximately correct. This research seeks to create basic knowledge about multivariate heavy-tailed distributions and to discover how to use that knowledge to create system models.

Objective: Develop an empirically based analytical framework for representing multivariate heavy-tailed distributions and create tractable computational procedures for calculating these distributions and for utilizing them in at least two DoD-relevant research areas.

Research Concentration Areas (RCAs): Interdisciplinary research in statistics, probability, mathematics and additional areas are needed to (1) Create an inherently multivariate (not tensor-product-of-univariate), mathematically consistent framework for multivariate heavy-tailed distributions. The framework should be applicable to a wide range of empirically observed data in a wide range of metric spaces including but not limited to Euclidean spaces. Include distributions with both simple and complex structure (for example, "spokes"). (2) Clarify how heavy-tailed distributions are represented through distribution functions, densities, quantiles, smoothness conditions and/or other methods. Compressed representation is preferred. (3) Create procedures for estimating multivariate heavy-tailed distributions from an observed data set. Clarify the uncertainty in and robustness of such estimates. (4) Using heavy-tailed statistical models, create global analytical system models and computational procedures in at least two DoD-relevant areas, e.g., communication (signal processing, systems engineering), compressed sensing (signal processing), information fusion (information sciences), social networks (social science), geometric modeling (computer science), cyber security (computer science) and risk analysis (systems engineering). Clarify the consistency of the global analytical models with the heavy-tailed nature of the statistical basis. Clarify the relation of the metrics, perhaps the l_1 and L_1 norms, used in the analytical system model to heavy-tailed distributions. (5)Identify or create empirical or other multidimensional heavy-tailed data sets for guiding the statistics research and for verification and validation (V&V) of the analytical models. Carry out V&V. Compare the capabilities of these models to models based on light-tailed distributions. (6) Clarify the computational expense of the representations and procedures of Research Concentration Areas 1 through 4, above. Computational tractability (scalability) is required.

Carry out comparisons with light-tailed-based procedures.

Research Topic Chiefs:
Dr. Harry Chang, ARO, (919) 549-4229, mouhsiung.chang@us.army.mil
Dr. John Lavery, ARO, (919) 549-4253, john.lavery2@us.army.mil.

ARO FY2012 MURI TOPIC #5

Submit white papers and proposals to the Army Research Office

Simultaneous multi-synaptic imaging of the interneuron

Background: It has been a goal of neuroscience to understand how individual neurons act as computational elements. Relatively simple models exist in e.g. the pyramidal cell with a large set of dendrites hosting many hundreds to thousands of synapses feeding excitation towards a cell body, integrating the activity into a fire/don't-fire "decision" at the axon hillock, sending out a spike or spike train down its single output axon. While this model is useful to explain e.g. motor neurons and some sensory neurons, it is inadequate for interneurons in the brain, where the most complex processing takes place. The fundamental problem is that interneurons are highly networked cells with multiple inputs and outputs. It has been to date impossible to record all the inputs and outputs from even a single living interneuron with synaptic levels of resolution in a living brain. While there is information on the morphological, physiological, and molecular properties of interneurons as a class and on their general synaptic connections, there is still little direct information on the functional roles of individual interneurons in cortical computations, and especially not on how each synapse relates to all the others within a single cell. Coupled with tagging via fluorescent molecules and/or chromophores and genomic modifications to control co-expression, electro-optical imaging may provide a solution, due to its ability to achieve subwavelength resolution across a relatively wide field of view. Recent research has developed a new localization-based imaging technique achieving almost isotropic subdiffraction resolution in 3D. The method appears to be relatively resistant to optical aberration and has demonstrated 3D imaging of neuron dendritic morphology with subdiffraction resolution. Moreover, network models are now sufficiently sophisticated to be able to handle the thousands of inputs and outputs simultaneously that would be needed to represent the totality of the synaptic traffic for an interneuron, including agent based models. Advances in genomic labeling, molecular tagging and fluorescence microscopy are also able to selectively transfect a particular class of neurons. Finally, sub-wavelength imaging over reasonable aperture sizes now permits the optical resolution to actually separate each and every synapse in an interneuron in the living system.

Objective: The goal is to explain and quantitatively model the entire set of neurotransmitter flows across each and every individual synapse in a single living interneuron. This would range from cell culture systems through model neural systems and if possible to the interneuron's normal anatomical environment in living mammalian brain while it is actively processing information.

Research Concentration Areas: This research addresses a fundamental "atom" of cognition – the individual interneuron – in a way that has never been attempted, both in its complexity (number of in/out links) and in its technical requirements (labeling and imaging). It seeks a functional and algorithmically precise description of the interneuron and its function. This will require work in at least the following fields: 1) synaptic fluorophores in living cells; 2) cell culture, ganglion preparations, brain slice and whole brain model systems; 3) subwavelength imaging; 4) computational modeling; 5) computational networks; 6) genomic marking of specific cell types, structures and molecules.

Research Topic Chiefs:
Dr. Elmar Schmeisser, ARO, (919) 549-4318, elmar.schmeisser@us.army.mil
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ARO FY2012 MURI TOPIC #6

Submit white papers and proposals to the Army Research Office

Revolutionizing High-Dimensional Microbial Data Integration

Background: A significant barrier to understanding the cause-effect relationship in natural systems increasingly requires analysis of complex Multiple-Input Multiple-Output (MIMO) data sets. In the physical sciences, such relationships are determined by general principles, such as conservation of energy or symmetry, but such principles are not yet available in the biological sciences. Consequently, we must develop the mathematical infrastructure necessary to make these connections. For example, a fundamental question in microbiology is how microbes adapt to new environments. In some cases the adaptation may involve jumping a species barrier to become an effective pathogen in another host. In others it may involve adapting from growth in a natural environment to growth *in vitro*. Whatever the change in environments, the input and output data complexity – multiple, heterogeneous, and correlated measurements – poses a challenge to interpret. Thus, novel methods for analyzing, integrating, and interpreting these complex MIMO data are sorely needed. Methods to analyze multiple-input, single-output data are available but have significant limitations; only recently, novel techniques, including predictor-variable grouping and prior biological knowledge, have resolved issues of statistical leniency on the one hand, in which false positives result, and an unwarranted conservatism, producing false negatives, on the other. Further, a recent hierarchical testing scheme for false discovery rate control has been shown to improve statistical power for high-dimensional, single-output data. Extending these new methods to multiple-output data will provide transformational new abilities. Microbiology presents special opportunities for these novel mathematical methodologies because it requires the interpretation of massive amounts of input and output data and the data can be quickly generated. Furthermore, the automation of parts of the analysis process will revolutionize the field by speeding up analysis by several orders of magnitude. For example, the opportunity would exist for real time blood sample analysis for medical vulnerabilities, guidance of health programs, and personal performance prediction.

Objective: The overall objective of this topic is to provide a fundamental understanding of microbial adaptation to new environments through the development of revolutionary high-dimensional data association methods that can handle complex, MIMO data.

Research Concentration Areas: Interdisciplinary research in statistics and applied mathematics is needed to (1) create new frameworks and models for associating MIMO data that minimize multiple testing, improve statistical power, and maximize generality. The frameworks should be able to handle multiple, heterogeneous, correlated outputs, as well as input data possessing equivalent complexity. Expertise from disciplines such as microbiology, biochemistry, molecular biology, and informatics are needed to (2) a) determine environmental growth conditions that must be explored to enable an understanding of microbial adaptation and collect all associated metadata; b) grow bacteria under the chosen well-defined, precisely-controlled conditions (temperature, nitrogen source, oxygen availability, enriched vs minimal media, etc.); c) use knowledge of bacterial physiology to anticipate revealing compositional data and collect this high resolution data such as genomics, proteomics, lipidomics, and glycomics from the resulting bacterial cultures. Methods from statistics, applied mathematics and computer science are necessary in order to (3) perform validation of the new models using data gathered in (2), including determination of model uncertainty, robustness, computational expense, and scalability.

Research Topic Chiefs:

Dr. Virginia Pasour, ARO, virginia.pasour@us.army.mil, 919-549-4254
Dr. Wallace Buchholz, ARO, wallace.buchholz@us.army.mil, 919-549-4230

ARO FY2012 MURI TOPIC #7

Submit white papers and proposals to the Army Research Office

Novel Nanostructures for the Controlled Propagation of Electromagnetic Energy

Background: Fundamental research involving metamaterials, quantum dots, plasmonic nanostructures, and other materials systems during the last decade has demonstrated the unique ability to selectively and actively control and attenuate electromagnetic energy from the far infrared (IR) through ultraviolet (UV) regions. Metallic nanoparticles, waveguides and similar structures have plasmonic resonances which absorb electromagnetic energy at characteristic frequencies. The absorption frequency is dependent on shape, size, orientation, and composition of the nanomaterial. The nanoparticles act as antennae that redirect, focus or otherwise re-radiate the incoming energy. Because this is a resonance phenomenon, the media is generally transparent over a broad frequency range, with one or more resonances that absorb at specific frequencies. A goal in the control of the propagation of EM energy is the design of a material that absorbs over a broad frequency range and is transparent at one or more specific frequencies. Recent developments in metallic nanostructures, composite nanoparticles, hybrid composite materials, excitonic materials and metamaterials, indicate that such control can be achieved. Significant and selective changes in absorption spectra, and therefore the associated transmission spectra, are possible by finely tuning the composition and size of multilayer materials. In addition, advances in negative index materials have generated systems that allow for enhanced transmission at specific wavelengths. For example, porous gold materials have been made in which absorption is highly dependent on the pore size. "Fishnet" structured negative index materials have been designed to allow for enhanced transmission at specific wavelengths. Double-shell composite nanoparticles made with J-aggregate layers (which are dye aggregates that exhibit J-bands in their absorption spectrum) have been developed and it has been demonstrated that significant changes in the line shape of the absorption spectrum is dependent on core size, presence of spacer layer, composition and size of spacer layer, and composition of the J-aggregate.

Objective: The objective of this MURI is to develop a fundamental understanding of nanomaterials to control the propagation of EM energy with a particular emphasis on materials that have a broad spectrum absorption with a narrow, selective window of transmission. Full modeling and predictive capabilities of the potential and limitations of novel materials with unique EM attenuation properties, such as those listed above, will be explored. A comprehensive understanding and the ability to control physical, mechanical, optical, electronic, and magnetic properties to tailor absorption, scattering, and reflection of specific wavelengths of light, including in free-space atmospheric propagation senarios, will be obtained using these novel nanomaterials. An understanding of the interactions of hybrid materials will also be developed.

Research Concentration Areas: Suggested research areas for the design and synthesis of new materials with unique chemical and physical properties that can be tuned for tailored absorption, scattering, and reflectance that demonstrate the ability to control the propagation of EM energy may include, but are not limited to the following: 1) anisotropically shaped materials, 2) multi-layered plasmonic materials, 3) quantum dots, 4) bandgap engineered nanoparticles, 5) conducting polymeric materials, and 6) negative index materials and metamaterials. A complete modeling and predictive capability of the potential and limitations of these materials should be developed and used to guide material design. Synergistic effects of emerging hybrid and multi-component systems should be explored. Surface functionalization techniques to control not only absorption, scattering, and reflectance but also atmospheric agglomeration and dispersion should be developed.

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ARO FY2012 MURI TOPIC #8

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Predictive Models of Cultural and Behavioral Effects on Societal Stability

Background: The goal of this research is to advance the capability of predictive modeling from individuals and small groups of individuals to societal level considerations of social and political stability. Recent events involving the diffusion of socio-political change across a broad range of North African and Middle Eastern countries emphasize the critically important role of social, economic and cultural forces that ultimately affect the evolution of socio-political processes and outcomes. These examples clearly demonstrate that radically different outcomes and chances for conditions of state stability result from the different institutional frameworks within these countries. It is well established in the social sciences that change in or evolution of institutions depends on the behavior patterns or culture of the people involved in them, while these behavior patterns depend in part on the institutional framework in which they are embedded. This dynamic interdependence of culture and institutional change means that the modeling of societal stability requires the coupling of individual modeling approaches describing such issues as trust and cooperation with models describing institutional dynamics. Trust and cooperation are critical to the function of institutions, and they depend on various elements of the culture (e.g., relatively high levels of trust in the military in Egypt helped facilitate larger, more organized demonstrations). Extensive case studies have demonstrated why a policy succeeded or failed by connecting its outcome with the culture, but there is no theory or comprehensive model which can predict such outcomes in advance. This MURI will seek to combine theoretical and modeling approaches which have shown success in dealing with cultural issues and with institutional change in order to address the holistic interdependence of culture and institutional dynamics. It will seek to extend the cultural approaches from application to individuals, families, and villages, to address stability of the larger social group. Traditional game theory is a common approach to analyzing institutional dynamics, however it assumes isolated, context-free strategic environments and optimum behavior within them, which severely limits it application to the evolution of cultural norms and ultimately institutional path dependence. Recent research is seeking to extend traditional game theory by, for example, introducing the concept of agents engaged in multiple simultaneous games, but this approach has been limited to simplified cases. Other research has advanced the understanding of institutional path dependence as a Markov process. Some success has been achieved using agent based simulation models, economic theory, public choice theory, social network analysis (e.g., social capital), and theories of trust, cooperation, and fairness. This MURI seeks to combine modeling and theoretical approaches from across the social, computer and mathematical sciences to make significant advances in our understanding of societal change and stability and to validate this understanding in real world situations using comparative, ethnographic, experimental and survey research.

Objective: To develop fundamental theoretical and modeling approaches to describe the complex interrelation of culture and institutions as they affect societal stability.

Research Concentration Areas: Research will involve the collection of original data in field or experimental settings. Research areas may include, but are not limited to 1) transformative integration of data, concepts, metrics and models from social, economic and political network analysis, 2) comparative research that models variations in the evolution of socio-political change as it relates to culture and institutional milieus as represented in the ongoing cases in

North Africa and the Middle East, 3) agent-based simulation approaches that make advances in the integration of related theories from across the social sciences at a variety of spatial and temporal scales, and 4) nonlinear modeling approaches that focus on emergent properties, particularly robustness, feedback mechanisms, tipping points and system cascades.

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AFOSR FY2012 MURI TOPIC #9

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Directional Eutectic Structures: Self-Assembly for Metamaterials and Photonics

Background: Metamaterials have physical properties determined by their organized structures rather than inherited directly from the material properties of atoms built by crystal chemistry principles. Synthetic structures or mesoscopic inclusions are building blocks of Metamaterials in comparison to the atoms and molecules of conventional materials. The properties of Metamaterials can be described by a small set of effective material constants if the operating wavelength is much larger than spatial period characterizing the particular arrangements of mesoscopic subunits. This requirement, imposed from the size of the building blocks, puts an upper limit for the properties and limits the discovery of unknowns. Hence, fabrication methods are required to achieve three-dimensional (3D) lattices with accuracies in the placement of building blocks that are better than a fraction of the wavelength. It is also essential to elucidate the role of defects in the periodic arrangement that changes the properties and interferes with the wave propagation. Ultimately, the research should make significant progress in bridging the gap between theory and experimental capabilities spanning wide a range of spatial length scales of building blocks. The current challenge for optical Metamaterials is to devise metholodologies that are able to provide nanoscopic accuracy in the positioning of the building blocks and 3D control over symmetry of the architecture. In particular, for metallodielectric Metamaterials to be useful in the visible range of the electromagnetic spectrum, extended 3D structures with lattice constants between 10 and 100 nm are required. Metamaterials with these constraints are difficult to synthesize with current micro lithographic technologies. There is lag in our understanding about the incredible diversity and complexity of DSE systems in large part from their ability to derive functional attributes organized structure while using a relatively small set of building blocks. The ability to design and create structures into three dimensions with precise control of nanomorphology is likely to have applications that extend beyond Metamaterials and may include 2D electron gas, new energy storage concepts, molecular separation and nanoreactors. The motivation of this MURI originates from the idea that directionally-solidified eutectic structures could bring features unavailable in conventional materials fabrication, such as (a) self-recognitions and defect rejection upon directional solidification (self-assembly), (b) the possibility of lattice self engineering using established material science methods (directed crystallization and phase transformation), (c) real-time changes of lattice constants using dopants and (d) science based understanding of coherent interfaces with the proven ability to generate extended structures with molecular precision.

Objective: The main objective of this initiative is to establish the framework required to develop a new class of Metamaterials capable of operation in a wavelength spectrum that has not been previously possible and to demonstrate Metamaterials exhibiting novel optical, or dielectric, or metallo-dielectric or plasmonic properties. To achieve the main objective, the MURI aims to elevate science and technology of directionally solidified eutectic structures as a possible means of combining the natural characteristics of self-assembling atoms during directional solidification and the physical properties of inorganic, coherent interface of the eutectic phases. Emphasis will be placed on building a scientific foundation, to design and create structures into three dimensions with the length scales that have not been achieved previously. This project will be inherently multidisciplinary and will include understanding/manipulation of the directionally solidified eutectic structures as well as chemical conversion of the nanoshape to mesoshape structures into a high-performance metamaterial.

Research Concentration Areas: The challenge of realizing the potential of directionally solidified 3D eutectic structure, as a metamaterial requires a seamless integration of a diverse collection of scientific and engineering disciplines, including crystal chemistry, physics, materials science, mathematics and high-resolution electron-optic and materials characterization and component design. Suggested research areas are as follows: (1) building the scientific foundation for the formation 3D self-assembly via directional solidification (defining the hierarchical organization of matter at length scales between 1 nm to 1000 nm) and provide scientific principles with proven ability to generate three-dimensional extended structures of hybrid metallic/nonmetallic components arranged with molecular precision, (2) bridging the gap between metamaterial performance of 3D eutectic structures and science based understanding of coherent interfaces, (3) understanding defect rejection upon directional solidification and the possibility of lattice self engineering using established material science methods (directed crystallization and phase transformation), (4) development of a mathematically rigorous theoretic framework for quantifying the polyphase eutectic structures through reliable and accurate descriptions of structures and shapes, and identifying sample distribution of shape descriptors to generate and predict structures which may revolutionize the metamaterial design and performance.

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AFOSR FY2012 MURI TOPIC #10

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Smart, Functional Nanoenergetics design from the atomistic/molecular scale through the mesoscale

Background: With significant advances in quantum chemistry and molecular dynamics over the last decade, as well as a broader understanding of the properties of nanomaterials, it may now be feasible to design *a priori* nanostructured reactive materials to perform a given function and then produce them in the laboratory according to the design, in order to avoid simply reacting in an uncontrolled fashion. The major challenge is to create the scientific foundation for the understanding of smart and functional nanoenergetics that is designed from the atomistic/molecular scale through the mesoscale. This understanding will lead to find activation mechanisms for smart nanoenergetics via temperature, pressure, the presence of a particular chemical compound, or external electromagnetic stimuli, such as an electrical field or light. By smart, it may be desirable to initiate a reaction at a particular temperature, to release a particular compound at a particular temperature, to transition from a deflagration to a detonation at a particular instant in time, to turn on or turn off a reaction, have tailored ignition properties, or to accelerate or slow a reaction with time or location. This goal requires the integration of modeling, materials science, combustion, and diagnostic communities to produce smart, functional nanoenergetics.

Much of the early research was concerned with the production of nanosized ingredients, and more recently, the passivation of these materials. Nanoenergetics has demonstrated both positive and negative effects when incorporated into propellants and explosives. During this period, the approach often taken was to see if the nanoenergetic material could be produced and then study how it would react. New materials are now available that will enable the development of new types of breakthrough nanoenergetic materials. For example, functionalized graphene sheets are now readily producible that have unique electrical, physical, optical, and chemical properties and can provide new directions for the development of reactive materials at both the nano and micron scales. Graphene sheets may be decorated with energetic materials such as energetic organics or metallic nanoparticles. Another approach is to encapsulate nanoscale fuels/catalysts within macroscopic crystalline materials or assemble micron scale structures that have nanoscale constituents. Although each material system offers something special, the highest reward is expected to be the design of nanoenergetics from the atomistic/molecular scale through the mesoscale.

Objective: The objective of this effort is two-fold. The first objective is to create the scientific foundation for the understanding of smart and functional nanoenergetics that are designed from the atomistic/molecular scale through the mesoscale. The second objective gains much of its power from the scientific approaches of first objective and aims to provide scientific pathways to generate micron size reactive materials with nanostructured features.

Research Concentration Areas: To develop such designer materials, significant research effort is required, examples include: (1) Combining state-of-the-art theoretical modeling techniques (that can resolve events occurring from the atomistic/molecular scale through to the mesoscale) with experimental diagnostic techniques (that can capture the reactive dynamics at femtosecond timescales to those that evaluate overall combustion performance) with novel nanotechnology fabrication techniques; (2) Provide uncommon elegance through scientific precision to investigate the response characteristic of nanoenergetic to external stimuli (i.e., thermal, electric, stress, acoustic, electromagnetic, and other fields); (3) Understand physics and chemistry of nanoenergetics and its relation to scale effects; (4) effect of morphology; (5) thermodynamic stability regimes; and (6) exact physics based understanding of kinetic effects.

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AFOSR FY2012 MURI TOPIC #11

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Managing Informational Complexity in Predictive Materials Science

Background: The fundamental challenge in materials science is to control the complex non-linear relations between structure, properties and processes. Understanding the intrinsic chemistry/composition, the microstructure of the material across scales, crystallography of phases, kinetic and diffusion aspects, and its mechanical behavior to mention just a few are all critical to understanding its macroscopic performance. In particular, *predictive materials modeling and design* requires computing and controlling the macroscopic property variability induced through many processes (thermal and deformation) that result in structure and property variability in multiple time and length scales. The models currently used to compute material properties are often phenomenological driven by multiscale data obtained experimentally and/or from more accurate simulators at finer time- and length-scales. Multiscale material models that account for structure variability at different scales pose significant mathematical and computational challenges not addressed by such traditional multiscale approaches. These issues become even more important as many problems of interest are posed as materials design problems in engineering and certifying materials leading to desired performance on the macroscale.

Objectives: This MURI is to establish mathematical approaches for stochastic and statistical framework for multiscale materials modeling that lead to discovery of new materials. Close partnership of researchers from material science and engineering with applied mathematicians and statisticians is required for building teams that can fully address the mathematical, physical and information theoretic challenges posed by this topic. The ultimate aim is to create a platform of new scientific enterprise to successfully resolve issues of complexity, variability across time and length scales, and allow for a dynamic integration and validation of mathematical predictions through new experimental methods that can enable rapid interrogation of structure and properties at different scales.

Research Areas: Particular topics of importance to this MURI include but are not limited to 1) Development of new multiscale multiphysics materials approaches addressing issues of the underlying model complexity (curse-of-dimensionality). Approaches based on probabilistic graphical models and information sciences are of particular interest.
2) Mathematical approaches for tractable and certified reduced-order microstructure models that can be validated by explicit experiments and/or driven by simulation of data. The end to end completeness requires integration of 3-Dimensional structural information techniques, i.e., x-ray computer tomography imaging, image segmentation and other techniques coupled to the length scales of mathematical, microstructural models.
3) Methods for on-line learning of high-dimensional process/structure/property relations of materials. Mathematical approaches that address issues of sparsity, locality and multiscale nature of the data are important. Examples of these methodologies include Bayesian regression using sparse kernels, locally weighted projection regression methods and many others.
4) Integration of the above techniques within a machine learning framework that allows rapid knowledge discovery and materials design in multiscale materials databases. The introduced techniques need to be able to produce quantifiable property variability utilizing a hierarchy of physical models of increasing complexity and association rules appropriate for multiscale and multiphysics materials models.

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AFOSR FY2012 MURI TOPIC #12

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Deep Atmospheric Optical Turbulence Physics and Predictive Modeling

Background: The objectives of this MURI are to discover the underlying physics that govern optical wave propagation through deep atmospheric turbulence and to develop and demonstrate practical predictive algorithms and models for this phenomenology that could be exploited to enable further exploration of deep turbulence effects. In long range atmospheric propagation scenarios, optical waves encounter distributed volume turbulence commonly referred to as deep turbulence that is not sufficiently well characterized and makes development of atmospheric mitigation techniques difficult. Example scenarios include long/slant horizontal propagation in free space optical communication, imaging, and laser propagation, and also for observation of low elevation satellites and stars. Currently this performance analysis is based on atmospheric measurements taken over path lengths of less than a few kilometers. The obtained data are then extrapolated to longer distances using Kolmogorov turbulence theory. Since the existing turbulence theory and models have been experimentally verified under only relatively weak (or moderate) scintillation conditions (Rytov number <1), the commonly used extrapolation of these models for performance assessment of long-range optical systems typically results in significant error. Adequate performance assessment is even more complicated in target-in-the-loop scenarios where design and control of the outgoing laser beam that scatters off a distant extended target is an unresolved challenge because of deficiencies in existing analysis and numerical modeling capabilities for target-return speckle-field propagation through deep turbulence.

Objective: This MURI should lead to the discovery of new physical effects related to laser beam propagation/scattering and image/data transmission in deep turbulence as well as rigorous modeling/simulation capabilities based on first-principles. The objectives of this MURI are aimed at dramatically improving the performance of long-range remote sensing, beam projection and imaging systems. A multidisciplinary research effort will bring physics, mathematics, optical sciences, fluid dynamics, laser sciences, experimental methods, and computational algorithm development disciplines together to develop a fundamental theoretical and/or experimental basis for assessment of the impact and mitigation of deep optical turbulence.

Research Concentration Areas: Suggested research areas include but are not limited to: (1) Theoretical and experimental efforts to study basic phenomenology and fill the existing knowledge gap in the physics of deep optical turbulence leading to critical revision and/or extension of the existing theories and development of new physics-based concepts; (2) Accurate theoretical tools (numerical, analytic and simulation) to model optical wave propagation through deep turbulence, dual pass propagation scenarios, and remote target interactions; (3) Development of new sensors and measurement capabilities to study turbulence physics at appropriate scales; (4) Exploration of physics-based beam control and mitigation concepts to demonstrate/confirm developed theories.

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AFOSR FY2012 MURI TOPIC #13

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Quantum Metaphotonics/Metamaterials

Background: Recently metamaterials have been fabricated at 1.5 μm and coupled to a highly excited semiconductor quantum well, prompting intense interest in studying and optimizing this interaction. Growth of quantum dots very close to the surface and emitting at 1.5 μm is a challenging task, as is identifying the most reproducible material system to use and measuring the interactions between metamaterials and semiconductor quantum structures. The solid state implementation of a strongly coupled, cavity-mode, two-level system is considered essential for the large-scale deployment of quantum information and quantum cryptographic systems. They will provide the enabling technology for a variety of quantum-optics-based components, such as single and entangled photons-on-demand sources and single-photon lasers, and they will probe the quantum-classical boundary at the most fundamental level. Metamaterials, on the other hand, offer the ability to control and confine light with engineered structures at the sub-wavelength scale to a degree unattainable by any other means. With the hybridization of these two technologies, the ability to confine, control and manipulate the light/matter interaction at the most basic quantum-mechanical level, in a scalable, robust platform, will lead to new technological opportunities unattainable by either technology separately. The advent of high-Q, small-volume photonic crystal cavities, along with quantum dots, has proven that semiconductors can provide a viable platform for accessing the strong-coupling regime of cavity quantum electrodynamics (CQED). Although a number of solid-state systems have been investigated which provide the required two-level state transition, the development of high-Q, small-volume optical cavities, incorporating metamaterials in which sub-wavelength meso-, micro-, and/or nanostructures may be assembled, offers unique opportunities for enhanced cavity/field interactions. Various aspects of the light/mater interaction, previously believed to be impossible, such as imaging beyond the diffraction limit, super-lensing and hyper-lensing, lead to the possibility of ultrathin, deeply-sub-wavelength waveguides, electrically-small antennas, and metatronic nano-antennas. Exploring metamaterials at the quantum level offers the opportunity to develop quantum-scale cavities for ultimate cavity/field coupling at increasingly shorter wavelengths. Other metamaterial-based approaches, such as photonic crystals, micro-rings, gratings or dielectric/metal hybrids have the potential to achieve a single-photon, strong-coupling regime associated with CQED, while providing the scalability, robustness and manufacturability required for the large-scale deployment of such quantum-optics-based systems.

Objective: Merge the fields of quantum optics and metamaterials in order to dramatically impact the field of CQED as it relates to semiconductor-based systems. Develop quantum physical approaches to the optical wave interaction with metamaterials based upon the light-matter interaction on their nanoscale constituents. Achieve large Purcell enhancement and strong coupling between a metamaterial cavity mode and a two-level system with the ability to scale the approach to an array format. Develop new material-growth techniques suitable for the generation of a discreet two-level system. Develop theoretical and computational algorithms and methods for modeling, analysis, synthesis, fabrication and characterization of metamaterials at the quantum level, both active and passive, in order to elucidate the light/matter interaction at the quantum-classical boundary.

Research Concentration Areas: This MURI topic will include multidisciplinary areas that require synergistic collaboration among theorists and experimentalists in fields such as physics, chemistry, material science, electrical engineering and computational science. It will bring together topics that may include, but are not limited to, nanofabrication, superconductivity, electronic band engineering, materials growth, quantum chemistry and quantum transport in order to understand, analyze, design, simulate and construct quantum metaphotonic/quantum metamaterial, chip-based quantum optical components.

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AFOSR FY2012 MURI TOPIC #14

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High Power, Low-Loss, Artificial Materials for Transformational Electromagnetics

Background: EM metamaterials are still in their infancy - one need only look at the controversies surrounding "cloaking" and "perfect lenses" to appreciate that a deep understanding of EM wave propagation through nontraditional media is not fully in hand. This is before the consideration of high-power, complex active gain media, or losses that might bring dispersion or nonlinearity into the problem. It is well recognized that materials design is a new frontier for novel, multifunctional RF devices. Research in this area is fueled by continuing growth in the commercial and defense industry for large bandwidth, high power, and compact systems. Example applications include: miniature conformal antennas on thin and flexible substrates for small M/UAVs; high gain antennas for portable devices enabling high data rate communications; non-reciprocal devices for covert operations; auto-scanning devices for tracking while suppressing co-site interference; multifunctional and reconfigurable apertures; and so on. It is believed that novel/exotic materials are therefore necessary to achieve optimal performance and miniaturization limits for both solid-state and vacuum RF sources. Metamaterials are one promising path for novel materials in RF devices. However, these advances have yet to result in metamaterials that can operate at the high power and energy levels for technologies such as radar, electronic warfare, and directed energy. The current generations of metamaterials are too lossy, and we find ourselves in the interesting scenario where metamaterials are working their way into commercial cell phone technology, but have not yet been hardy enough to serve in DoD radars, or next generation directed energy devices. This MURI looks to address this fundamental question of high power and energy density metamaterials.

Objective: Recent approaches have demonstrated that three-dimensional anisotropy is critical to realizing new spectral responses never observed before with natural materials. The metamaterials community has often focused on scattering, where isotropic response is a key performance driver. If one is willing to relax this constraint, a new class of metamaterial can be developed with aperiodic and anisotropic features. More specifically, anisotropic media introduces new parameters that can be exploited to realize novel electromagnetic phenomena Research is aimed at discovering new arrangements and processes for mixing or arranging natural as well as artificial materials to construct controllable anisotropic dielectric and magnetic composites. The goal is to provide a new class of materials enabling innovative directions in high power RF design.

Research Concentration Areas: This topic will require close collaboration between mathematicians, physicists, electrical engineers, and material scientists. As magnetic and dielectric materials are generally lossy at RF frequencies, particular emphasis is on the realization of properties with much lower loss. Multiferroics are potential approaches for realizing low loss anisotropic media. Also, fresh arrangements of magnetic/dielectric materials, nanomaterials, nano-clusters, 3D textiles, and organic materials may offer new approaches to realizing novel properties. Materials having controllable features for re-configurability are also of interest. The proposed research should have as a goal the development of first-principles-based guidance for the design and optimization of miniature, broadband, or multifunctional RF devices (sources, antennas, microwave couplers and filters, matching networks, lenses, self scanning arrays, antenna radomes, etc) as well as materials suitable for inclusion in high power, large bandwidth software radio, radars, and electronic warfare devices.

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ONR FY2012 MURI TOPIC #15

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Morphable Dynamic Information Processing

Background: Single neurons can display a wide range of behaviors including spiking, bursting, intermittent firing and chaotic responses. Neural ensembles can possess higher organizational phenomenon including brain waves organized through neural avalanches and transient chaotic synchronization. Chaotic synchronization has been discovered to play an important role in coordinating neural activity from the visual cortex to the motor cortex. At higher levels of activity, transitions between sleep states have been shown to involve self-tuned self-organized critical behavior. These phenomena show that information processing in the brain is not just anatomical, but also dynamical. Neural firing depends on trans-membrane ionic currents, but computation can be accomplished just as well with electronic elements. While many ideas of information processing can be bio-inspired, we will be implementing information processing in electronic networks, not in biological cellular materials. The topology of the network, e.g., small world, Erdos-Renyi, or scale-free, etc and the balance between excitation and inhibition are to be explored, as well as, the stability and sensitivity of the dynamics. Spatio-temporal complex networks and the nonlinear dynamics they support will be key to developing more biological-like types of computation and information processing. One recent advance has been to show that chaotic oscillators can be voltage controlled to select and stabilize chaotic orbits. This allows the construction of morphable logic gates where voltage control can determine how zeros and ones input into a gate get converted to an outgoing response. For example, exploiting chaos an XOR gate can be switched into a NAND gate or any other gate. Neural synapse strength changes in response to activity and the same can be sought for electronic morphable gates. In addition, there are savings in heat generated and space occupied as information can be feed repeatedly back N times to the same gate whose logic can change with each pass rather than using N gates. On the mathematical side, dissipative dynamical systems have been studied for low degree of freedom systems that are shown to support chaotic fractal attractors and fractal neural coding has been shown to be involved in hippocampus and olfactory systems. A key ingredient of neural systems is transient behavior and this is inconsistent with the older idea of computing with low dimensional attractors where the system can get stuck. New research focus on higher dimensional (degree of freedom) nonlinear dynamical systems where escape (itinerant attractor hopping) is eased and transient chaos can be supported. The role of noise, such as stochastic resonance, will be explored as an enabler of attractor switching for decision making.

Objective: Exploit rich nonlinear dynamical behaviors employing electronic neurons and morphable computing architectures to explore new approaches and paradigms for computation and information processing that can shed light on the concept of cognition.

Research Concentration Areas: <u>Nonlinear Physics and Mathematics</u> to study complex morphable networks and the rich collection of dynamical behaviors that they can generate and support from transient temporal chaos to global activity; <u>Neuroscience</u> to bring bio-inspired architectures, organization, and neural responses associated with cognition, <u>Electrical Engineering</u> to design and build chaotic circuits and networks that can self-tune to optimize tasks such as pattern recognition; Computer Science to program novel morphable networks of chaotic logic gates.

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ONR FY2012 MURI TOPIC #16

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Extended-Range Environmental Prediction Using Low-Dimensional Dynamic Modes

Background: The Navy's Task Force Climate Change has identified improved predictions of the physical environment as a necessary component to allow for resource and operational planning for the Navy. As the entire DoD begins to assess potential impacts due to changes in the variability of climate and weather patterns over lead times from multiple months to multiple years, an improved capability to forecast these changes will benefit all services by enabling better assessment of different mitigation and adaptation strategies. Current methods for predicting the future state of the operational environment use numerical models that are meant to simulate the behavior of the system by directly representing or parameterizing all relevant physical processes. This leads to complex, high-order models with millions of degrees of freedom. While such models can often provide realistic simulations of synoptic weather systems, it is not clear that they offer the best possible approach to making environmental predictions on longer time scales (3-12 months).

Low-frequency modes of variability observed in different components of the earth's physical system (atmosphere, ocean, cryosphere, and land surface) suggest that useful longer-range forecasts (with 3-12 month lead times) may be possible if the complex behavior of the earth system can be stochastically reduced into a much lower-dimensional phase space. Examples of such modes include the El Nino–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Madden-Julian Oscillation (MJO) and the Pacific–North American pattern (PNA), which all represent variations in weather and climate patterns that can impact operational conditions across the globe. A variety of methods could be explored to significantly reduce the dimensionality of complex coupled numerical models and the available observational data, while still capturing the high-frequency impacts and the longer-term predictability of the low-frequency patterns.

Objective: Explore the development of improved seasonal (3-12 month) forecasts through the reduction of complex high-resolution numerical models or observational time series into lower-dimensional stochastic models that provide useful projections of operationally-relevant environmental parameters. The proposed effort should investigate the impact and utility of knowledge about the periodicity, non-linearity, and "memory" of the different physical components on the behavior of the earth system in a reduced-order phase space, and result in improvements in extended stochastic predictions of the global operational environment.

Research Concentration Areas: The work under this topic will concentrate on (1) development of reduced-order stochastic models of the operational environment, (2) exploration of global or regional predictability using low-mode models of the earth system at a variety of forecast lead times (up to one year), (3) improved understanding of the factors leading to potential predictability at various lead times, and (4) development of techniques to incorporate realistic noise signals into reduced order models to adequately capture natural environmental variability.

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ONR FY2012 MURI TOPIC #17

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A New Way to Dissipate Shock Wave Energy from Detonations

Background: The Navy currently mitigates damage from blast shock waves by employing cellular materials that mechanically crumple to dissipate energy or by layering elastomers on metals surfaces that modulate shear banding – presumably by undergoing a second order phase transition through the glassy state. New ways of dissipating the energy from multi-frequency, hypersonic shock waves are desired for protecting personnel and machinery, especially protecting warriors from traumatic brain injury. This MURI proposes a completely new approach to protection from shock wave damage: to deplete the shockwave of its energy by using the blast energy to drive a harmless chemical reaction. If the shock wave energy can be dissipated this way, that wave is no longer a threat. It is well known that chemical reactions having a negative volume of activation, $-\Delta V^{\dagger}$, i.e., where the volume of the transition state is smaller than that of the reactants, can be driven to completion hydrostatically at high pressures (*Chem. Rev.*, **1998,** 98, 2167). The working hypothesis of this MURI is that those same reactions can be driven by explosive-driven shock waves and one report seems to confirm this (*J. Phys. Chem.*, **1996,** 100, 18775).

Objectives: The purpose of this MURI is to explore the underlying chemical physics of bond formation induced by high strain rate shock waves. The objective is to examine how energy is captured, transferred and directed towards chemical product development using experiment and simulation. Specific aims include: (1) identifying classes of reactions that lead to high chemical yields and characterizing the underlying variables leading to such reactivity. (2) Providing a scientific basis for the mechanism of energy uptake and redistribution in molecules and how that energy is directed towards bond making rather than bond breaking. (3) Examining the congruence of detonation wave speeds (km/sec) with timescales of chemical reactions, especially for reactions where translational and/or rotational motions are required prior to reaching the transition state, e.g., in bi-molecular reactions or tethered uni-molecular reactions. (4) Assessing the likelihood of new reaction channels opening under the severe conditions of a blast shock wave (high strain rate, high T and GPa pressures), and, determining if Woodward-Hoffmann products are observed. (5) Identifying the factors responsible for wave propagation through inhomogeneous, chemically reaction systems, and, developing an understanding of how that impacts the chemistry taking place.

Research Concentration Areas: A balanced, interdisciplinary program consisting of (1) Synthesis; (2) Chemical analysis; (3) Spectroscopy; (4) Theory; (5) Mechanics.

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ONR FY2012 MURI TOPIC #18

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Programming Biology to Attain Non-Natural Functions

Background: The goal of synthetic biology (SynBio) is to enable the design, engineering and production of biological systems to *reliably* perform specific functions. It promises new approaches for discovery of materials, bio-manufacturing, smart sensors/diagnostics, therapeutics, and even fuels. The building block concepts of digital electronics have been applied to devise functional, interoperable genetically-encoded 'parts' that may be hierarchically assembled into circuits and networks with desired functions. Unlike digital electronics, however, SynBio still lacks robust approaches for design and modeling of biological circuitry and networks as computations, and to attain specific computable functions with biology, especially if the desired function does not exist or is uncharacterized in Nature. This is in part due to: (1) the inherent complexity present in biological systems, where interactions with synthetic genetic circuits are poorly understood, (2) limited robust datasets from well-characterized interoperable functional 'parts' and modules, and (3) a lack of rapid, high-throughput approaches for systematically testing and analyzing genetic circuit variants (including 'failures')[1,2]. This topic will provide an opportunity to devise new strategies for overcoming these limitations and to develop desired, non-natural functions.

Creation of non-natural functions using SynBio have largely involved directed evolution or modification of known functions. The next step is to devise strategies for eliciting functions which have no well-characterized natural correlate, such as sensing or generation of non-chemical, non-current-based signals. Examples include the detection (or production) of acoustic or radiofrequency signals, optical signals outside the visible spectrum, or sensing of magnetic fields. These functions will enable external control of the organism, multiplexing of circuits, and new opportunities for future surveillance applications. Non-diffusible signals are also needed to test function of engineered circuits within host chassis[2].

Although many clever bioengineered circuits/systems have been built and tested[3,4], these have occurred largely through brute force approaches that rely on manual or semi-automated experimental methods to validate their functions. The challenge is to automate these methods, to analyze large libraries of biological variants (e.g., organisms, genes), and create an integrated framework for a bio-CAD/CAM, making functionally-*correct*-by-design possible.

Objectives: To expand the set of fundamental tools available for SynBio, to include automation, new functional biological 'parts', and create frameworks for describing, modeling, and reasoning about properties of assemblies of these biological 'parts.'

Research Concentration Areas: include but are not limited to: (1) Genetic circuits that yield a non-natural functions such as detection or generation of non-chemical signals (e.g., radiofrequency waves, sound, non-visible light, magnetic fields). (2) High-throughput, automated and rapid methods for characterizing sequence, structure and function, as well as "interoperability", of biological parts/modules/circuits within their biological hosts, and (3) Improved modeling and computational tools for synthetic biology. It is highly desirable that experimental approaches for RCA's 1 and/or 2 are designed to best inform the data needs of computational scientists. Developing quantitative, dynamic models for newly identified biological parts or modules using existing programs[5] or through development of new computational tools would be highly desirable.

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ONR FY2012 MURI TOPIC #19

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Predicting the Behavior of Complex, Non-Deterministic Autonomous Systems and Mixed Autonomous/Manned Teams under Realistic Assumptions

Background: Autonomy technologies are currently being developed to perform functions such as coalition/team formation, task allocation, mission planning/replanning, decision-making/control, organic perception, and interaction/collaboration with human and other engineered agents. However, there is currently a significant gap between research in autonomous systems and the availability of analytic methods to understand and predict their behavior under realistic assumptions. These new autonomy approaches are designed to perform tasks that may require years of training by highly skilled operators and can be very challenging to assess even in humans. The theoretical approaches involved are complex and it is not feasible to exhaustively test them over all possible inputs, states, modes, and environmental conditions, as well as all the ways that human operators, users, teammates, or bystanders may interact with them. Examples of particularly challenging methods include ones that are highly nonlinear, non-deterministic, adaptive/learning, converge in unpredictable time-scales, vary their levels of autonomy, use more natural and mixed-initiative methods to interact with humans, are implemented in a decentralized way across multiple agents, have some reliance on communication networks, and make critical decisions based on integrated multi-modal sensor information of varying degrees of reliability. The use of these technologies may be non-intuitive for operators or for other human beings sharing the same operational space, lead to complex interactions between components, mode switching problems, and poor reliability across the full range of environments and mission tasks they may be used for. In a worst case, lack of ability to predict their behavior may prevent their fielding altogether. There are a number of approaches that have been examined in different research programs to address pieces of this problem including reachable sets, nonlinear stability methods, robust control theory, bounding non-deterministic/complex elements in various ways, probabilistic methods, modeling the contribution of humans in the loop using control or queuing methods, and adaptively generating test sets with optimization approaches to attempt to find worst case situations. However, while these approaches have had success within particular narrow areas, the broader and more general aspects of how to solve this type of problem are currently unknown. For example, there are significant limitations with solving the reachability problem for complex high-dimensional systems and many probabilistic approaches may not be effective if sources of uncertainty are not well behaved (e.g., not Gaussian).

Objective: To develop new analytic and test methods and principles to predict the behavior of complex autonomous control systems and identify boundary conditions and worst-case combinations of inputs, modes, states, environmental factors and human interactions. This includes autonomous systems capable of emergent behavior, adaptation, and life-long learning as well as modeling complex human interactions. To develop analytical methods that can be utilized by autonomous systems to assess the validity of learning/adaptation in real-time and to assist unmanned vehicle operators to better understand the capabilities and limitations of their systems in particular situations.

Research Concentration Areas: This topic requires collaboration among the fields of control theory, computer science, robotics/unmanned vehicle autonomy, computational intelligence, machine learning, mathematics, and human factors/cognitive science. Research focus areas: (1) The development of models of human interaction with autonomous systems that are suitable for predicting human/machine performance including for high-level cognitive tasks, (2) Analytic approaches that can predict the behavior of complex autonomous systems under realistic assumptions despite characteristics such as biological inspiration, nonlinearity, nondeterministic algorithms, decentralized control, organic perception within control/decision-making loops, and complex human interactions (operators, teammates, bystanders), (3) Methods for testing complex systems that increase the likelihood of finding worst-case situations. This may involve intelligent/learning methods to guide the search for test cases that cause pathological responses and methods inspired by how human competence is assessed for similar functions.

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ONR FY2012 MURI TOPIC #20

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Extreme Electron Concentration Materials and Devices

Background: Advances in solid state devices for electromagnetic energy conversion have dramatically enabled many new approaches for improved energy efficiency in applications from DC to RF. Low on-resistance (Ron) is a key device parameter which has driven research in solid state devices to investigate new materials with increased electron density and conductivity. This evolution is marked by the performance gains from compound semiconductors such as Gallium Arsenide (GaAs) compared to Silicon, and more recently the wide bandgap semiconductors such as Gallium Nitride (GaN). The enhancement of electron concentration, coupled with high breakdown voltages and mobility, have enabled electronics which offer unprecedented efficiency for power switching devices and orders of magnitude improvement in bandwidth, efficiency and frequency for RF devices. However, there has been relatively little consideration given to materials beyond the conventional set of semiconductor materials in the conventional field effect transistor device topology. Recent discoveries suggest the possibility to move beyond this materials portfolio to achieve groundbreaking performance. Driven by polarization discontinuity, oxide systems have demonstrated electron concentrations in the range of 1E14 -1E16 cm^{-2}, which are 1-3 orders of magnitude higher than the possible concentrations in conventional semiconductors. High carrier concentrations are attractive in conventional electronic devices, where the possibility exists for faster, more efficient devices in both the energy and RF regimes. However, the concentration is also approaching the density of metals but with the ability to switch, which opens the possibility of new devices and new physics to explore. One additional exciting possibility is reconfigurable "metal"-dielectric waveguides of use in novel plasmonic devices, which enable interfacing environmental EM waves to electronic circuits as well as provide new techniques for processing information via hybrid optical-electronic circuits.

Objective: The objective is to discover unconventional materials structures that exhibit controllable electron concentrations in excess of 1E14 cm^{-2} (or 3D equivalent) and explore their potential for use in electronic devices at room temperature. Materials should be non-metallic and outside of currently well-funded research topics such as the LAO/STO interface or carbon-based electronics. Very low carrier mobility will limit impact of very high electron concentration on overall conductivity, so consideration of research directions must include the complete set of carrier transport properties of the materials. Controllable implies that the carrier density can be varied through approaches such as separation between band edges and Fermi levels through external control.

Research Concentration Areas: This topic area revisits fundamental semiconductor devices with a new set of starting materials. Suggested research areas include but are not limited to: (1) first principles theory for modeling of materials, (2) materials scientists to develop growth techniques, (2) experimental and theoretical device physicists and (4) physics and engineering of the electromagnetic (EM) environment within and outside the solid state environment.

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ONR FY2012 MURI TOPIC #21

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Super-hydrophobic Surface for Skin Friction Drag Reduction in High Reynolds Number Turbulent Flow

Background: Super-hydrophobic surfaces (**SHS**) are actively being explored as an energy saving concept that could reduce skin friction drag of various systems, including ships and underwater vehicles (UUVs, torpedoes, submarines). The skin friction drag is a fundamental source of mechanical energy loss for objects moving in a fluid. Therefore, the management of skin friction has been a topic of considerable interest as engineers strive to improve the energy efficiency and performance of ships and submerged vehicles. This is especially true for high Reynolds number (**Re**) flows where turbulent boundary layer flow drastically increases the near-wall momentum transport and resulting skin friction.

Recent advances in micro- and nano-engineering have led to the development of micro- and nano-structured SHSs that would allow *slip* (*shear free*) between the liquid and solid surface through formation of gas pockets, thus reducing the skin friction drag. The degree to which surface adhesion (and therefore the no-slip condition) can be reduced is characterized by the "slip-length". The "slip length" is directly related to skin friction reduction. These surfaces have been demonstrated in reducing the skin friction in low **Re** micro channel flow (typically $<10^3$) in the laboratory with the slip length of 10's of microns. At higher **Re** ($>10^5 - 10^8$), however, none of these surfaces have been successful to date in reducing the skin friction. Slip lengths must increase by at least one order of magnitude if such surfaces can reduce the skin friction in high Re turbulent flows (*e.g.* large-scale flows).

Advances in a fundamental understanding of the physical mechanism that reduces the skin friction of SHS in high **Re** turbulent flow are critical for realization of the profound potential for SHS for future applications. The advances would then lead to new designs and analysis techniques that would enable fabrication of large scale SHS for meaningful applications.

Objective: The objective of this MURI is to understand the physical mechanism by which the skin friction is reduced due to interaction of near-wall turbulence and SHS in high Reynolds number (**Re** $> 10^5$) turbulent flow. Once the physical mechanism is revealed, the research effort will then focus on what combination of near wall surface morphology, physical and chemical properties, and flow processes can lead to the largest reduction in skin friction in the high **Re** flow. A multidisciplinary research effort will bring physics, chemistry, materials science, fluid mechanics, and nano- and micro-manufacturing together to design and characterize the SHS performance.

Research Concentration Areas: Suggested research areas may include but not limited to the following: (1) theoretical analysis of the near-wall turbulent flow to understand the interaction with the SHS that would result in skin friction reduction; (2) development of computational approaches, including modeling of micro- and nano-surface structures, that would reveal the turbulent flow physics of skin friction reduction of SHS; and (3) detailed experimental study of the near-wall turbulent flow at high Reynolds number (**Re** $> 10^5$) using advanced optical and/or other appropriate methods that could reveal the mechanism of skin-friction reduction of SHS in high **Re** turbulent flow.

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