**Disruption Opportunity**

**DARPA-PA-19-02-01**

**Nature as Computer (NAC)**

## I. Opportunity Description

The Defense Advanced Research Projects Agency (DARPA) Defense Sciences Office (DSO) is issuing a Disruption Opportunity (DO) inviting submissions of innovative basic or applied research concepts in the technical domain of alternative computing. This DO is issued under the Program Announcement for Disruptioneering, DARPA-PA-19-02. All awards will be made in the form of an Other Transaction (OT) for prototype project. The total award value for the combined Phase 1 base and Phase 2 option is limited to $1,000,000. This total award value includes Government funding and performer cost share (if required). Proposers must include cost share (if required) for each proposed Phase in their proposal.

Many computation problems relevant to Department of Defense (DoD) missions do not lend themselves to being easily solved by conventional computer processors. For example, predicting the behavior of complex physical processes often involves modeling multiphysics dynamical processes spanning across large spatial and temporal scales. Realizing multiphysics modeling at scales relevant in real world applications demands computation with a huge number of cores, massive concurrency, and a correspondingly massive data transfer capacity. Without a change in computing technology, the level of power consumption, fault tolerance, and cost necessary for large-scale multiphysics modeling may be enormous and impractical.

In contrast, Nature solves certain computation problems that span large dimensions and scales with higher efficiency. An illustration of this is Levinthal's Paradox: in nature, proteins fold spontaneously at short timescales (milliseconds) while it has been shown that the protein folding problem formulated in the digital domain, a complex optimization problem, is NP-complete.

The actual protein folding mechanism is still unclear, but a possible explanation to this paradox is that protein sequences have built-in features that "enable a shortcut that bypasses what would otherwise be a nearly hopeless unaided search for the final three-dimensional structure."[1] It is postulated that the physical forces of chemical bonds and a set of non-local contacts constrain the state space to smaller regions and the computation to a smaller set of trajectories. In other words, Nature couples dynamical processes and physical constraints to accomplish effective, if specific, computation. Here dynamics provide computing power and constraints limit the solution space, which together provide the essential efficiency improvements. The NAC program takes the view that this coupling is a crucial element underlying Nature's efficiency and precision. The NAC program seeks to explore this coupled paradigm to develop powerful new forms of computation.

### A. Objective/Scope

This DO invites proposers to submit innovative research concepts that exploit the interplay between complex dynamical behaviors and intrinsic properties of materials to develop novel

[1] Bergasa-Caceres, F., et al., Nature's Shortcut to Protein Folding, *J. Phys. Chem. B*20191232144634476

computing models for the purpose of tackling current hard computation problems. Proposals must target a class of computation problems and identify a specific computational challenge that, for fundamental reasons (not those that will be solved by next-generation CMOS technologies) cannot be solved with the required performance and within the desired resource limits. NAC will lay the foundation for advancing new theories, design concepts and tools for novel computing substrates, and metrics for comparing performance and utility, as well as demonstrate the feasibility of solving the proposed challenge problem with orders-of-magnitude improvements over state-of-the-art.

Recent research shows that many dynamical processes may be configured to provide for controlled computation[2]. An often neglected aspect about such computing is that they occur in physical systems[3]. In Nature, the physical processes *are* the computation. This is in contrast to our classic digital computation models such as the Turing model, in which computation is abstracted in mathematical/logic notions, away from physical substrates. Physical substrates are then engineered to implement the abstracted computation.

The focus of the NAC program differs from recent nonconventional computing research efforts that seek novel material substrates for realizing abstract, general-purpose computation. NAC seeks a different strategy: its primary goal is to identify and/or engineer physical properties in materials to implement desired computation directly. An example is computing Voronoi diagrams using chemical reactions[4]. Such computing would be highly efficient since it takes place "for free" as the result of intrinsic physical properties.

NAC is interested in new computation models and concepts that address computation problems poorly suited to, or functionally unexplored with classical models. The ability to harness physical processes for purposeful computation has been demonstrated at lab-scales in a range of physics domains[5]. NAC aims to bring this concept of computing to offer breakthrough capabilities in real world applications beyond lab-scale feasibility. In other words, the proposed effort should not be focused on whether a particular unconventional computation can be realized, but whether it *should* and indeed *must* be realized.

Example classes of challenging computing problems include, but are not limited to, multiphysics simulations (e.g., hypersonic thermo-aeroelastic load forecasting, turbulence modeling),[6] materials for massively distributed sensing and control (e.g., airfoils with a highly expanded performance envelope, soft robotic contact control), and robust network optimization and analysis. Proposals should provide a quantitative analysis on the potential magnitude of improvement relative to traditional computing metrics, and delineate the ways in which the proposed new computation models can better solve the specific proposed challenge problem.

The following types of proposals are considered non-responsive to the NAC objectives:

- Proposals that offer general-purpose computing platforms (e.g., new neuromorphic computers, novel hardware for reservoir computing, or new quantum computing).

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[2] Tanaka, G., et al. "Recent advances in physical reservoir computing: a review", *Neural Networks* (2019).

[3] Stepney, S. "The neglected pillar of material computation." *Physica D: Nonlinear Phenomena* 237.9 (2008): 1157-1164.

[4] Costello, B., et al., "Calculating voronoi diagrams using chemical reactions." *Advances in Unconventional Computing*. Springer, Cham, 2017.

[5] Hughes, T. W., et al. "Wave Physics as an Analog Recurrent Neural Network", *arXiv preprint arXiv:1904.12831*(2019).

[6] Estakhri, N, M, et al. "Inverse-designed metastructures that solve equations", *Science* 363.6433 (2019).

- Proposals that only offer a novel Non-Turing computation theory without addressing a challenge problem as described above.
- Proposals with Phase 2 application demonstrations that are merely to establish a capability of solving classic computing problems in new ways but do not demonstrate substantially new or improved capabilities (e.g., recognizing handwriting digits using a chemomechanical oscillator network).
- Proposals that seek to derive novel computation models from natural processes for implementation in conventional computers (e.g., new biologically-inspired algorithms).
- Proposals in which computation models are not applicable to a general class of computation problems (e.g., implementing a specific PDE).

### B. Technical Area Descriptions

Proposers must address the two interdependent Technical Areas (TAs) described below for each of the program phases.

Technical Area 1 (TA1): Theory and Design

For TA1, proposers must detail their innovative approach for identifying and deriving computation models from physical systems, either natural or engineered, in the context of a performer specified challenge computation problem. Research for TA1 shall lay the foundation for the development of theories, design concepts, and design tools to establish ways of exploiting such computation models. TA1 research shall explore questions such as: What types of dynamical physical systems are suitable for the targeted computation challenge problem? What are the capabilities and limitations? How are such systems programmed? What are the inputs and outputs? If the dynamical processes do not occur naturally, how do we artificially engineer them?

Technical Area 2 (TA2): Application Demonstration

For TA2, proposers must detail their approach towards developing a prototype implementation suitable for demonstrating the capability of the computation model to address the proposed challenge problem. TA2 efforts shall develop the appropriate mapping between the model(s) and the application, develop control and readout mechanisms, implement the computation prototype, train/program the model(s), and perform an experimental evaluation and performance analysis. Simulated demonstrations are acceptable for computation models that require engineering of new materials.

### C. Program Structure

The NAC program shall have two phases: The focus of Phase 1 will be a Feasibility Study, during which performers will derive computation models for a class of natural or artificially engineered material systems and establish exploitation methods (TA1), as well as perform a preliminary application demonstration (TA2). Phase 2 will shift the focus towards a Proof of Concept demonstration, during which performers are expected to demonstrate experimentally solving their challenge computation problem(s) (TA2) using the material systems developed in Phase 1, while continuing to refine their computation theories/models (TA1). Proposals must address both TAs.

Proposals submitted to DARPA-PA-19-02 in response to this DO must be UNCLASSIFIED and must address two independent and sequential project phases (a Phase 1 Feasibility Study (base) and a Phase 2 Proof of Concept (option)). The periods of performance for these phases are 9 months for the Phase 1 base effort and 9 months for the Phase 2 option effort. Combined Phase 1

base and Phase 2 option efforts for this DO should not exceed 18 months. The Phase 1 (base) award value is limited to $500,000. The Phase 2 (option) award value is limited to $500,000. The total award value for the combined Phase 1 base and Phase 2 option is limited to $1,000,000. This total award value includes Government funding and performer cost share (if required). Proposers must include cost share (if required) for each proposed Phase in their proposal.

**D. Schedule/Milestones**

Proposers must address the following Research Project milestones and deliverables, along with fixed payable milestones in their proposal. The task structure must be consistent across the proposed schedule, Task Description Document (TDD), and the Vol. 2 - Price Volume. Proposers must complete the "Schedule of Milestones and Payments" excel attachment provided with this DO Opportunity as part of submitting a complete proposal and fulfilling the requirements under Vol. 2 Price Volume. Performers can supplement the required milestones with additional milestones if needed, and should propose estimated funding for each. If selected for award negotiation, the fixed payable milestones provided will be directly incorporated into Attachment 2 of the OT agreement ("Schedule of Milestones and Payments"). Proposers are encouraged to use the TDD template provided with this DO Opportunity, which will be Attachment 1 of the OT agreement.

Phase 1 base effort fixed payable milestones shall include, at a minimum, the following (proposers could provide additional detail, specific to their proposed project, as necessary):

- Month 1: Report providing a description of the targeted computation problem; an analysis of the computation challenges and the current state-of-the-art; a description of the proposed novel computation model concept(s) that exploit dynamical processes and physical properties of the material substrates to affect the desired computation for the targeted computation problem; a preliminary analysis on the expected advantages of the proposed approaches over the current state-of-the-art towards solving the targeted application problem; and, a detailed research plan.
- Month 3: Report describing the preliminary mapping of the proposed computation problems to the computation models.
- Month 5: Interim report describing the computation model designs, analysis of the computation behaviors and properties, analysis of computation capabilities and limitations, descriptions of input and output control mechanisms, and a description of the learning mechanisms that enable engineering the computation models for specific application problems.
- Month 7: Report describing preliminary simulation or experiment validation of the feasibility of the computation models for the targeted application problem and a preliminary Phase 2 demonstration design.
- Month 9: Final report documenting the findings and results from the Phase I work, including detailed descriptions of the computation models and theories, a detailed analysis of the advantages of the proposed models, and details of the Phase 2 demonstration design.

Phase 2 option fixed payable milestones shall include, at a minimum, the following (proposers could provide additional detail, specific to their proposed project, as necessary):

- Month 10: Report providing an updated research and development plan based on the Phase 1 research outcome and PM feedback.

- Month 12: Report on the initial implementation and preliminary simulation/experiment results.
- Month 14: Interim report describing the application demonstration prototype, the simulation/experiment results, a quantification of performance, and a comparison against state-of-the art.
- Month 16: On-site demonstration of the application prototype.
- Month 18: Final report documenting the findings and results from the Phase 2 work, including updated computation theories and models, application demonstration design and implementation, experiment results and performance analysis, analysis of the scalability of the performance observed in the prototype, and potential challenges in actual implementations.

For planning and budgetary purposes, proposers should assume a program start date of November 15, 2019. Schedules will be synchronized across performers, as required, and monitored/revised as necessary throughout the program.

All proposals must include the following meetings and travel in the proposed schedule and costs:

- To foster collaboration between teams and disseminate program developments, a two-day Principal Investigator (PI) meeting will be held approximately at kick-off and every six months, with locations split between the East and West Coasts of the United States. For budgeting purposes, plan for four two-day meetings over the course of 18 months: two meetings in the Washington, D.C. area and two meetings in the San Francisco, CA area.
- Regular teleconference meetings will be scheduled with the Government team for progress reporting as well as problem identification and mitigation. Proposers should also anticipate at least one site visit per phase by the DARPA Program Manager during which they will have the opportunity to demonstrate progress towards agreed-upon milestones.

### E. Deliverables

Performers will be expected to provide at a minimum the following deliverables:

- Program kick-off and PI meeting presentation material and other presentation materials as requested by the Government.
- Milestone reports detailed in the Schedule/Milestones Section.
- On-site demonstration of the application prototype in Phase 2.
- Other negotiated deliverables specific to the objectives of the individual efforts. These may include registered reports, experimental protocols, publications, data management plan, intermediate and final versions of software libraries, code, and APIs, including documentation and user manuals, and/or a comprehensive assemblage of design documents, models, modeling data and results, and model validation data.

## II. Award Information

Selected proposals that are successfully negotiated will result in award of an OT for prototype project. See Section 3 of DARPA-PA-19-02 for information on awards that may result from proposals submitted in response to this notice.

Proposers must review the model OT for Prototype agreement provided as an attachment to DARPA-PA-19-02 prior to submitting a proposal. DARPA has provided the model OT in order to expedite the negotiation and award process and ensure DARPA achieves the goal of Disruptioneering which is to enable DARPA to initiate a new investment in less than 90 days

from idea inception. The model OT is representative of the terms and conditions that DARPA intends to award for all DO Awards. The task description document, schedule of milestones and payments, and data rights assertions requested under Volumes 1, 2, and 3 will be included as attachments to the OT agreement upon negotiation and award.

Proposers may suggest edits to the model OT for consideration by DARPA and provide a copy of the model OT with track changes as part of their proposal package. Suggested edits may not be accepted by DARPA. The Government reserves the right to remove a proposal from award consideration should the parties fail to reach agreement on OT award terms and conditions. If edits to the model OT are not provided as part of the proposal package, DARPA assumes that the proposer has reviewed and accepted the award terms and conditions to which they may have to adhere and the sample OT agreement provided as an attachment, indicating agreement (in principle) with the listed terms and conditions applicable to the specific award instrument.

## III. Eligibility

See Section 4 of DARPA-PA-19-02 for information on who may be eligible to respond to this notice.

## IV. Opportunity Responses

### A. Proposal Content and Format

All proposals submitted in response to this notice must comply with the content and format instructions in Section 5 of DARPA-PA-19-02. All proposals must use the templates provided as Attachments to the PA and the "Schedule of Milestones and Payments" Excel Attachment provided with this DO and the and follow the instructions therein.

Information not explicitly requested in DARPA-PA-19-02, its Attachments, or this notice may not be evaluated.

### B. Proposal Submission Instructions

Responses to DARPA-PA-19-02-01 shall be submitted through electronic upload to DARPA's BAA Portal (https://baa.darpa.mil).

DARPA will acknowledge receipt of complete submissions via email and assign identifying numbers that should be used in all further correspondence regarding those submissions. If no confirmation is received within two business days, please contact: NAC@darpa.mil to verify receipt.

When planning a response to this DO, proposers should take into account the submission time zone and that some parts of the submission process may take from one business day to one month to complete (e.g., registering for a Data Universal Numbering System (DUNS) number or Tax Identification Number (TIN).

**Electronic Upload**
First time users of the DARPA BAA Portal must complete a two-step account creation process. The first step consists of registering for an extranet account by going to the URL listed above and selecting the "Account Request" link. Upon completion of the online form, proposers will receive two separate emails; one will contain a user name and the second will provide a temporary password. Once both emails have been received, the second step requires proposers to go back to the submission website and log in using that user name and password. After accessing the extranet, proposers may then create a user account for the DARPA Submission website by

selecting the "Register your Organization" link at the top of the page. Once the user account is created, proposers will be able to see a list of solicitations open for submissions, view submission instructions, and upload/finalize their proposal.

Proposers who already have an account on the DARPA BAA Portal may simply log in at https://baa.darpa.mil, select this solicitation from the list of open DARPA solicitations and proceed with their proposal submission. Note: proposers who have created a DARPA

Submission website account to submit to another DARPA Technical Office's solicitations do not need to create a new account to submit to this solicitation.

All full proposals submitted electronically through the DARPA Submission website must meet the following requirements: (1) uploaded as a zip file (.zip or .zipx extension); (2) only contain the document(s) requested herein; (3) only contain unclassified information; and (4) must not exceed 100 MB in size. Only one zip file will be accepted per full proposal. Full proposals not uploaded as zip files will be rejected by DARPA. Technical support for the DARPA Submission website is available during regular business hours, Monday – Friday, 9:00 a.m. – 5:00 p.m. Requests for technical support must be emailed to BAAT_Support@darpa.mil with a copy to NAC@darpa.mil. Questions regarding submission contents, format, deadlines, etc. should be emailed to NAC @darpa.mil. Questions/requests for support sent to any other email address may result in delayed/no response.

Since proposers may encounter heavy traffic on the web server, DARPA discourages waiting until the day proposals are due to request an account and/or upload the submission. Note: Proposers submitting a proposal via the DARPA Submission site MUST (1) click the "Finalize" button in order for the submission to upload AND (2) do so with sufficient time for the upload to complete prior to the deadline. Failure to do so will result in a late submission.

### C. Proposal Due Date and Time

Proposals in response to this notice are due no later than 4:00 PM on September 3, 2019. Full proposal packages as described in Section 5 of DARPA-PA-19-02 must be submitted per the instructions outlined in this DO *and received by DARPA* no later than the above time and date. Proposals received after this time and date may not be reviewed.

Proposers are warned that the proposal deadline outlined herein is in Eastern Time and will be strictly enforced. When planning a response to this notice, proposers should take into account that some parts of the submission process may take from one business day to one month to complete.

## V. Proposal Evaluation and Selection

Proposals will be evaluated and selected in accordance with Section 6 of DARPA-PA-19-02. Proposers will be notified of the results of this process as described in Section 7.1 of DARPA-PA-19-02.

## VI. Administrative and National Policy Requirements

Section 7.2 of DARPA-PA-19-02 provides information on Administrative and National Policy Requirements that may be applicable for proposal submission as well as performance under an award.

## VII. Point of Contact Information

Jiangying Zhou, Program Manager, DARPA/DSO, NAC@darpa.mil

## VIII. Frequently Asked Questions (FAQs)

All technical, contractual, and administrative questions regarding this notice must be emailed to NAC @darpa.mil. Emails sent directly to the Program Manager or any other address may result in delayed or no response.

All questions must be in English and must include name, email address, and the telephone number of a point of contact. DARPA will attempt to answer questions publically in a timely manner; however, questions submitted within 7 days of the proposal due date listed herein may not be answered.

DARPA will post an FAQ list under the DO on the DARPA/DSO Opportunities page at http://www.darpa.mil/work-with-us/opportunities?tFilter=&oFilter=2&sort=date. The list will be updated on an ongoing basis until one week prior to the proposal due date. In addition to the FAQ specific to this notice, proposers should also review the Program Announcement for DO General FAQ list on the DARPA/DSO Opportunities page under the Program Announcement for Disruptioneering (DARPA-PA-19-02).