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7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Pittsburgh
123 University Place
B21 UCLUB
Pittsburgh, PA 15213 -2303

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UU	UU	UU	UU		19b. TELEPHONE NUMBER 412-648-9250

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RPPR Final Report
as of 20-Dec-2019

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INVESTIGATOR(S):

Name: Anna S. Balazs
Email: balazs@pitt.edu
Phone Number: 4126489250
Principal: Y

Organization: **University of Pittsburgh**
Address: 123 University Place, Pittsburgh, PA 152132303
Country: USA

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Phone: (412) 648-9250
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STEM Degrees: **STEM Participants:**

Major Goals: Computers have undergone a radical transformation from machines that occupied an entire room to the portable laptops and handheld devices that are common features of current, everyday life. These transformations were enabled by advances not only in computer science, but also discoveries in materials science. The development of the computers of the future will also necessitate a close coupling between and progress in the fields of materials and computer science. Namely, the computational platforms, or “fabrics” of the future, will not resemble the current hardware, which encompasses arrays of hard electronic components, but rather, will resemble actual fabrics that will lie in close contact with or could be draped over the human body. Notably, the largest human organ is the skin and hence, the most effective modes of human-machine interactions might very well involve designs that can take full advantage of the skin/computer interface. Clearly, this will necessitate the development of new materials that are lightweight and mechanically compliant or deformable, and can sense and respond to human touch and motion in order to perform a level of computing that will enrich the life of the human wearing this fabric.
To meet these important goals, it is vital to transform computing platforms from desktops or even hand-held mobile appliances fabricated from a large collection of heterogeneous parts, to a computational fabric built with new material systems and implementing new computational paradigms. Addressing this challenge requires that researchers mesh boundaries between materials and computer science, enabling the computer and the material to be one and the same entity, thus creating “materials that compute”.

To help nucleate this new field of research, we held a workshop that brought together scientists with a broad range of backgrounds. Fundamental advances in science and technology often come about through synergistic interactions between individuals working in different disciplines. Approaching complex scientific problems from different perspectives can lead to significant breakthroughs that could not be accomplished in isolation. The development of new materials systems for computing exemplifies an area that critically needs input from different disciplines in order to realize their potential. It was an opportune time to hold this workshop due to recent advances in non-Boolean computing and the understanding of fundamental principles that underlie non-linear dynamical behavior in chemical systems. Importantly, we can exploit this synergy of cross-disciplinary interest and research to pave the way for creating computing materials.

Accomplishments: We brought together the disparate communities that can contribute to this revolutionary field. In particular, we brought together researchers working in chemistry, chemical engineering, electrical engineering, computer science, materials science, and soft robotics. The workshop lasted one and a half days. The group was intentionally kept relatively small (about 20 researchers) to facilitate interactions among all the participants.
The first day was devoted to short talks by researchers who are already helping to nucleate this field (such as

Nader Engheta at University of Pennsylvania), as well as innovators in “programmable matter” and unconventional computing. We also invited speakers who focus on using chemistry to program information. While DNA has been used in this context, we examined other chemical systems that can be used to achieve this goal.
The next day was allocated to outlining the overall challenges in this area. Our aim is to forge new collaborations within the group to help address these challenges. Working as a group, we attempted to:
- Formulate means to harness the intrinsic properties of the materials to achieve the functionality of the device.
- Design devices where the physicochemical properties of the system (e.g., the synchronization of the oscillations) will allow the “physics to do computing” .
- Determine unique combinations of materials or material properties that will produce the desired functionality.
- Establish how the structural organization of the combined materials affects the ability to perform computation.
- Clarify how we will “perform computing” by providing the three primitive resources of functional operators, storage, and communications.
- Determine how a coupling across different energy domains (thermal, mechanical, optical, chemical) and external stimuli can be used to drive the device.
- Establish routes for enabling autonomous functionality of the device.

Training Opportunities: The training opportunities will emerge from the development of a new field and training researchers in this exciting new area. The ability to create materials systems that can sense the environment, process information, and react to complex stimuli will enable new devices that can interface with humans to provide enhanced quality of life, by providing tactile, temperature, and photonic inputs to smart clothing, robotic manipulators, and possibly prosthetic limbs. The field of designing biomimetic devices for human-centric activities is still very much in its infancy and the advent of “materials that compute” can enable progress in this critically needed area.
The development of “materials that compute” will revolutionize the design of soft robots by enabling these machines to ultimately exhibit the dynamic and adaptive functionality of biological systems. Current robots require microprocessors and microelectronics to direct and power the devices to perform specific tasks. For the robot to alter its function, the programmer must alter the code. Hence, such robotic systems are not particularly adaptive; they cannot spontaneously modify their functionality in response to environmental changes. The advent of materials systems that can autonomously sense, communicate, and compute will enable the creation of devices that dynamically and autonomously change their behavior in response to external cues. Thus, the development of computing materials can ultimately enable the creation of highly responsive, self-regulating, and cooperative soft robotic systems.
While the design of “materials that compute” will necessitate the development of chemical systems that can encode information, our vision extends beyond the principles of “Molecular Informatics”. Namely, we take a systems level view, where the chemicals are just one vital component of the materials system. Hence, the systems of the future will integrate chemistry and the inherent properties of the materials’ components to form a computing device, which can store and recognize patterns.

As part of training, we worked together as a group to attempt to:
- Articulate what we mean by “computing”
- Clarify how we will “perform computing” by providing the three primitive resources of functional operators, storage, and communications
- Formulate means to harness the intrinsic properties of the materials to achieve the functionality of the device.
- Design devices where the physicochemical properties of the system (e.g., the synchronization of the oscillations) will allow the “physics to do computing”.
- Determine unique combinations of materials or material properties that will produce the desired functionality.
- Establish how the structural organization of the combined materials affects the ability to perform computation.
- Determine how a coupling across different energy domains (thermal, mechanical, optical, chemical) and external stimuli can be used to drive the device.
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Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

RPPR Final Report
as of 20-Dec-2019

PARTICIPANTS:

Participant Type: PD/PI
Participant: Anna Christina Balazs
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

University of Pittsburgh

Swanson School of Engineering
Department of Chemical and Petroleum Engineering

940 Benedum Hall
Pittsburgh, PA 15261
412-648-9250
Fax: 412-624-9639
Email: balazs@pitt.edu

May, 25, 2018

Dear All:

We would like to invite you to a small, by-invitation-only, two-day workshop funded with support from the US Army Research Office on the topic **"Designing 'Materials that Compute' ".** This workshop will be held at Triangle Research Park, Durham, NC during **Jan. or Feb., 2019**. With the aid of the ARO funding, we will be able to cover some fraction of your travel costs.

The challenge prompting the workshop is to transform computing platforms away from desktops or even hand-held mobile appliances fabricated from a large collection of heterogeneous parts to a computational "fabric" built with new material systems and implementing new computational paradigms. The ideal computing materials would "sense, compute and respond" in a relatively autonomous manner, harnessing the innate properties of the materials themselves. One means of achieving these objectives is to take advantage of the co-evolution of energy-transducing, stimuli-responsive materials, and modes of computation, such as non-Boolean associative processing, which can exploit these responsive materials. ***In effect, we are attempting to nucleate a new field of "materials that compute"; that is, systems where the computer and the material are one and the same entity.***

The purpose of this workshop is to bring together the disparate communities that can contribute to this revolutionary field. To this end, we will bring together researchers working in chemistry, chemical engineering, electrical engineering, computer science, materials science, and soft robotics. We anticipate that the workshop will last two days. The group will intentionally be kept relatively small to facilitate interactions among all the participants.

We would very much value your input on this exciting topic. To insure your attendance, please let us know what **two week days in January and February 2019** will work best for you. (Please exclude Jan. 27-Feb. 1 and Feb. 4-8.) One possible suggestion is **Feb. 12-13, 2019**. Please let me know by **June 8st** (two weeks from now) and cc: your response to Ms. Joni Carlin at jdc9@pitt.edu.

The first day will be devoted to short talks by researchers who are already helping to nucleate this field, as well as innovators in "programmable matter" and unconventional computing. We will also invite speakers who focus on using chemistry to program information. While DNA has been used in this context, we will examine other chemical systems that can be used to achieve this goal.

The second day will be allocated to outlining the overall challenges in this area. Our aim is to forge new collaborations within the group to help address these challenges. Working as a group, we will investigate how to:

- Formulate means to harness the intrinsic properties of the materials to achieve the functionality of the device.
- Design devices where the physicochemical properties of the system (e.g., the synchronization of the oscillations) will allow the "physics to do computing".
- Determine unique combinations of materials or material properties that will produce the desired functionality.
- Establish how the structural organization of the combined materials affects the ability to perform computation.
- Clarify how we will "perform computing" by providing the three primitive resources of functional operators, storage, and communications.
- Determine how a coupling across different energy domains (thermal, mechanical, optical, chemical) and external stimuli can be used to drive the device.
- Establish routes for enabling autonomous functionality of the device.

Thank you and best wishes,

Anna C. Balazs
Distinguished Professor of Chemical Engineering
John A. Swanson Chair in Engineering
Chemical Engineering Department
University of Pittsburgh, Pittsburgh, PA 15261

Nader Engheta
H. Nedwill Ramsey Professor
Electrical and Systems Engineering,
Physics and Astronomy,
Materials Science and Engineering,
Bioengineering
University of Pennsylvania
Department of Electrical and Systems Engineering
200 South 33rd Street
Philadelphia, Pennsylvania 19104-6314, U.S.A.