NSF Workshop on Papertronics: Paper-based Electronics for the 21st Century
Final Report
September 12-14, 2016 in Arlington, VA

Summary

A workshop held in Arlington, VA under the auspices of the National Science Foundation reviewed the status and future directions of devices built in/on/with paper as a key component. The workshop organizers Aaron Mazzeo/Rutgers University, Andrew Steckl/University of Cincinnati, and Christina Swanson/Juno Therapeutics worked with Usha Varshney/NSF to assemble a group of experts in various aspects of the field, which included academics, scientists from industry and government labs, entrepreneurs, and program managers in several government funding agencies.

The field of "papertronics" encompasses devices based on a combination of fluidics, electronics, photonics, mechanics, and chemistry. In the last decade, there has been a five-fold increase in the number of published articles on "paper electronics." Paper-based electronics have focused on the fabrication of circuits, supercapacitors, batteries, fuel cells, solar cells, transistors, microwave electronics, digital logic/computation, displays, force-sensing MEMS, user interfaces, optically transparent substrates, substrates with high strength, wearable devices, and biomedical devices based on electrical, chemical, mechanical, magnetic, and photonic interactions. These devices with their associated physics and processing are relevant to society's ongoing efforts in environmental sustainability, safety, communication, health, and performance.

As a material, cellulose-based paper is fibrous, renewable, and bendable with the most common forms coming from trees. Paper consisting primarily of polymeric cellulose is a multi-scale material with millimeter-scale structures built on interlocking micro and nano fibers. This fibrous network permits wicking/handling of liquids for electro-chemo-opto-mechanical sensors and devices. Paper also has tunable stress-strain relationships, which can be soft with similar mechanical impedance to biological tissue or hard with a theoretical elastic modulus for cellulose nanocrystals higher than steel and similar to Kevlar. Cellulosic fibers are also compatible with metallization, conductive coatings, nanotubes, and graphene for patterned electrical properties.

This workshop brought together research leaders in academia and government labs, along with those in small and large businesses, to discuss the state of the art and potential future directions in papertronics. The goal of the workshop was to address potential future directions for research and scalability within three themes or working groups:

Theme 1: *Electronic Devices, Packaging, and System Architectures*

Theme 2: *Healthcare and the Environment*

Theme 3: *Physics and Processing*

These working groups met together to address current scientific challenges and make recommendations for future research direction. Based on the findings of the working groups and discussions at the workshop, we make the following recommendations for future research efforts:

Recommendation 1: *Improve understanding, leverage, and prediction of multi-scale behaviors of electrical, photonic, mechanical, thermal, fluidic, magnetic, and chemical properties of fibrous paper-based materials.*

Recommendation 2: *Create and invent methods for packaging, preparing, storing, and maintaining reagents and fabricated components on paper-based materials for sensitive and accurate functionality in controlled and extreme environments.*

Recommendation 3: *Explore new fabrication techniques or modify existing manufacturing methods for tunable, scalable, and sustainable production of targeted physical properties and papertronic devices.*

Recommendation 4: *Work toward design rules and descriptions for physical limits of paper as a material for electronic devices.*

Recommendation 5: *Initiate broad, cross-cutting programs in papertronics based on scientific fundamentals in <u>integration and assembly</u>, <u>processing and material selection</u>, and <u>tunable properties</u>, which integrate vertically with each other, along with <u>scalable devices and applications</u> (see roadmap).*

To visualize how these recommendations fit together, we have created the roadmap in the attached image, which relates tunable properties to future scalable devices and applications through integration and processing. While not exhaustive, this roadmap provides a representative summary of how research themes might fit together to lead to scalable applications based on fundamental scientific exploration. Scientific exploration in horizontal categories (e.g., patterning, stacking, and interconnects) will have limited impact without considering the neighboring vertical hierarchal elements (e.g., the functional requirements for the desired scalable devices and processing/tunable properties of the fibers feeding into integration and assembly). Thus, we suggest the evaluation of future research efforts in the context of vertical and horizontal contributions to this roadmap.

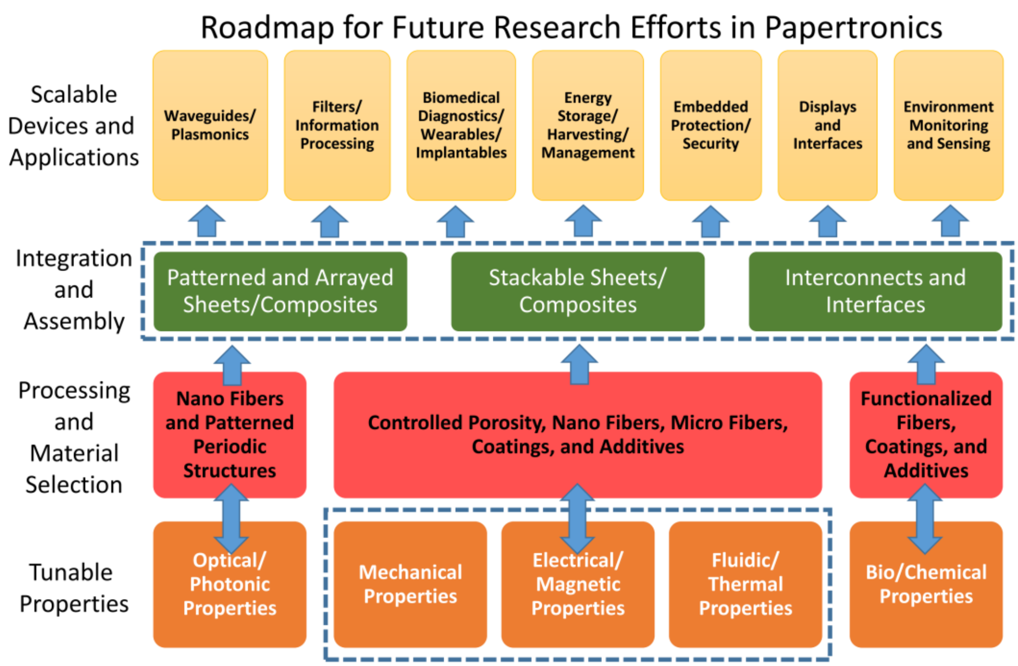

Fig. 1: Papertronics roadmap, illustrating horizontal and vertical integration for paper-based systems.

Findings from Working Groups

Working Group 1: Electronic Devices, Packaging, and System Architectures

Working Group (WG) 1 focused on making recommendations for Theme 1: Electronic Devices, Packaging, and System Architecture. The scribes were Christina Swanson from Juno Therapeutics and Babak Ziaie from Purdue University. During their discussions, three topics emerged: (1) challenges of moving from printed circuit boards (PCBs) to paper; (2) powering of devices; (3) manufacturing of devices and packaging.

Moving from PCBs to Paper

Moving from a PCB to a paper substrate requires an adaptation of materials. The primary issue encountered was the inherent surface roughness of a porous material. Here, the group felt that new methods to smooth the surface of the paper or methods to create multi-layered or complex papers with porous centers and smooth surfaces are needed. The 2nd issue with developing paper electronics was the cost and paucity of available inks. Research into developing new inks with novel properties, semiconducting properties, and low costs are necessary. The 3rd issue identified is determining the properties of the papers and inks available. Towards simplifying this process, a materials repository that standardizes paper and ink properties needs to be established. This repository will be charged with identifying the most important properties to measure, establishing the best technical methods to measure these properties and disseminating this information to the public. The 4th item had to do with moving from PCB to paper, namely issues with devices/packaging in wet environments or devices that incorporate microfluidics. The discussion examined how to separate fluid components the electronic components. Research questions in this area could evaluate different membrane-friendly methods (i.e., no seepage) to seal the electronics from moisture.

Powering of Devices

Powering of devices is a current issue facing electronics in paper and packaging. Our group identified some possible options for powering electronics, which included radio-frequency (RF) coupling, batteries, fuel cells, and cellulose itself as fuel. While each of these options may work depending on the application, WG1 favored further research focused on liquid batteries and power storage (to enhance RF power capabilities). Further, we recommend studies comparing the voltage/current produced, duration and stability of the power supply to inform which power source to use with each application.

Manufacturing of Devices and Packaging

Manufacturing of paper electronics is still novel and not accomplished at scale. WG1 approached the issue of manufacturing at scale in two ways. First, companies promote developing paper electronic device manufacturing as separate smaller lines and then integrating them into the larger packaging manufacturing line. Notably, full integration of paper electronics into a single packaging manufacturing line, while desired by numerous companies, has not been achieved as far we know. This lack of integration into a manufacturing line is because the equipment to do so has either not been developed yet or is not commercially available. Second, for research purposes, the group thought that establishing smaller manufacturing techniques in the laboratory early on would speed up the lab-to-factory time.

In addition to issues with equipment and incorporation into packaging lines, the group identified two areas in manufacturing that might require further research. First, because paper electronics often consist of multiple layers, there was agreement that alignment and vias (electronic connections) were of top concern. Second, simulation of how paper electronics will be placed on packaging and interact with the environment inside/outside the package as well as the packing itself is lacking. Third, determine achievable/needed feature dimensions and device density that are relevant to "papertronics (as opposed to conventional semiconductor electronics).

Working Group 2: Healthcare and the Environment

WG2 was a broad-based group consisting of ~20 participants from academia, government labs, funding agencies, and industry. The scribe was Sameer Sonkusale from Tufts University.

Several key themes evolved from the discussions of WG2 regarding the properties of paper-based devices for healthcare & environment:

- Define and determine the fundamental limitations: sensitivity to signal and ambient; noise level; minimum/maximum fluid sample volume; shelf life.
- Define the main advantages of paper-based diagnostics: low cost of materials; no accessories (e.g., pumps) needed; ease-of-use; disposability (prevent contamination & spread of disease).
- Identify the special characteristics of paper for healthcare/environment umbrella: adjustable porosity & capillary flow rate; storage & rehydration of various immobilized reagents; creasing/folding ability for 3D structures.
- Determine the present limitations of paper-based diagnostics: mostly qualitative, sensitive to moisture, one-time measurement (vs. continuous monitoring).

Detailed discussions on the applications of paper-based devices in the healthcare & environment fields led to several broad observations & preliminary conclusions:

- Consider dual-use military/commercial applications to build on military programs and develop broad-based commercial markets;
- Monitoring of biomarkers is an area of great interest to several user communities: armed forces, 1st responders, athletes, wellness/fitness groups, groups needing point-of-care/use disease monitoring;

The capillary effect in paper is the key property, but for overall devices, one should consider performance/cost trade-offs involved in combining paper with textiles, plastic, and even Si electronics.

Working Group 3: Physics and Processing

WG3 focused on the physics and processing of paper-based electronics. The scribe was Michael Mansfield from EMD Millipore. This working group based most of their discussion and recommendations in the context of the process flow for producing paper. The steps for paper production include raw material processing, fiber processing, modification, manufacturing of the paper itself, secondary modification and functionalization, and conversion to final format/devices.

In processing paper, there are opportunities to address fundamental physical questions, which include the study of the following:

1. *Modeling of multi-scale structural and interfacial properties of fibrous composites*
2. *Tuning properties from varied feedstock and processed fibers in pulps/slurries*
3. *Functionalization of fibers, surfaces, and substrates*
4. *Linking fabricated pulps and fibers to scalable processing techniques*
5. *Scalable paper processing to meet new technological demands (e.g., implantation, biosensors, photonics, sterilization, handling of fluids) not addressed by current practices*
6. *Bridging gaps and predictions between small papermaking platforms, pilot lines, and high-volume production*
7. *Patterning, cutting, and converting manufactured substrates into scalable devices*
8. *Working toward the incorporation and understanding of new and existing standards to enable efficient communication and transfer of experimental and numerical results*

Recommendations

The working groups focused on electronic devices, packaging, and system architectures; healthcare and the environment; and physics and processing. With the discussions and presentations associated with these three themes, we make the following recommendations:

Recommendation 1: *Improve understanding, leverage, and prediction of multi-scale behaviors of electrical, photonic, mechanical, thermal, fluidic, magnetic, and chemical properties of fibrous paper-based materials.*

Recommendation 2: *Create and invent methods for packaging, preparing, storing, and maintaining reagents and fabricated components on paper-based materials for sensitive and accurate functionality in controlled and extreme environments.*

Recommendation 3: *Explore new fabrication techniques or modify existing manufacturing methods for tunable, scalable, and sustainable production of targeted physical properties and papertronic devices.*

Recommendation 4: *Work toward design rules and descriptions for physical limits of paper as a material for electronic devices.*

Recommendation 5: *Initiate broad, cross-cutting programs in papertronics based on scientific fundamentals in <u>integration and assembly</u>, <u>processing and material selection</u>, and <u>tunable properties</u>, which integrate vertically with each other, along with <u>scalable devices and applications</u> (see roadmap).*

Recommendation 1: Multi-scale Behaviors and Properties

In general, the papertronics community will benefit from reviewing the vast literature and standards (e.g., International Organization for Standardization (ISO) and Technical Association of the Pulp and Paper Industry (TAPPI). These standards serve as guidelines for high-volume production or established laboratory-scale procedures, and thus have relevance to studying and developing new processing techniques. Nonetheless, leveraging recent developments in multi-scale modeling, simulation, and physical phenomena will improve fundamental scientific understanding of fibrous materials for electronic applications.

Many of the papertronic publications in the last decade have described methods to place electronic components on paper, fill the interstices of fibrous media, or manipulate the porosity and dimensions of the fibers themselves. These approaches will continue to be powerful processing techniques, and there are opportunities to understand and model the resulting properties in more detail and with models that might be shared openly in the papertronics community. By so doing, we anticipate the discovery of new methods to manipulate electrical, photonic, mechanical, thermal, fluidic, magnetic, and chemical properties of paper. With their periodic fibrous structure spanning the nano, micro, and macro scales, there are opportunities to relate small-scale features to bulk properties and vice versa. As developments in semiconductor-based electronics led to scientific discoveries in solid-state physics, understanding how charges flow about fillers, functionalized fibers, or the organic fibers themselves will be important for future efforts in miniaturization and increased functionality of papertronic devices. Likewise, analogies linking flowing charge to photons, stress, phonons, fluids, and other fundamental physical building blocks in a fibrous medium are also relevant.

Recommendation 2: Sensitivity and Functionality in Varied Environments

As efforts to industrialize academic and laboratory-based demonstrations proceed, it will be essential to understand the fundamental science associated with preserving functionality in varied environments. Cellulose-based paper is hydrophilic and is very sensitive to humidity. While there are techniques for limiting this sensitivity, they come with the tradeoff of impeding fluid flow or altering electronic properties of the paper. Also, many of the reagents being used for biomedical applications require storage or processing at temperatures above 25°C. Even though paper itself is resilient to fluctuating temperatures (i.e., its ignition temperature is ~230 °C), fundamental scientific efforts for evaluating and creating new methods for maintaining functionality under varied conditions will allow papertronics to make impacts as scalable devices. In some cases, it may even be possible to leverage inherent environment-dependent properties (e.g., swelling) as sensors.

Recommendation 3: Fabrication and Manufacturing for Sustainable Applications

Over the past decade, there have been innovative techniques for patterning, stacking, and packaging paper-based devices using off-the-shelf components in many cases. In some circumstances, these techniques will be adequate for future applications. Nonetheless, there are opportunities to invent new methods for fabricating and manufacturing papertronic devices. As printing has proven scalable for books, magazines, and newspapers, additional rate-independent techniques (e.g., screen printing, stenciled masks, and lithography) merit attention. However, as volumes for niche-based applications may be low, new techniques also merit attention. With the current difficulties associated with scaled production of nano fibers, sustainable nano manufacturing also merits attention.

Recommendation 4: Design Rules and Fundamental Physical Limits of Paper

Paper is attractive for many future applications, but there is a lack of design rules to guide its use in electronic applications. These design rules might relate processing conditions to resulting properties. They might also suggest that yet-to-be-observed properties be attainable with new processing, morphologies, or functionalization. Efforts toward understanding the fundamental properties and physical limitations of paper will go beyond directing future research efforts but also guide the design of engineered applications.

Recommendation 5: Initiation of Broad, Cross-Cutting Programs in Papertronics

With its ability to handle wicking fluids, accept fillers, be compatible with functionalizing biochemistry, display colorimetric responses, possess tunable fibrous morphology, and biodegrade, paper will continue to receive attention as a material for multiple device applications. To realize the full potential of papertronics, we have outlined the four previous recommendations as broad topics for research efforts. Our final recommendation is that there be one or more broad, cross-cutting programs to fund efforts that would fit within these recommendations and the included roadmap.

While not exhaustive, this roadmap provides a representative summary of how research themes might fit together to lead to scalable applications based on fundamental scientific exploration. Scientific exploration in horizontal categories (e.g., patterning, stacking, and interconnects) will have limited impact without considering the neighboring vertical hierarchal elements (e.g., the functional requirements for the desired scalable devices and processing/tunable properties of the fibers feeding into integration and assembly). Thus, we suggest that future research efforts be evaluated in the context of vertical and horizontal contributions to this roadmap. A cross-cutting program might have the following characteristics.

Title: Papertronics Science and Engineering for Advanced Sustainable Devices
Key Words: paper-based electronic devices; healthcare and environmental monitoring; processing of fibrous materials

INTRODUCTION AND DESCRIPTION

The field of "papertronics" encompasses devices based on a combination of fluidics, electronics, photonics, mechanics, and chemistry. In the last decade, there has been a five-fold increase in the number of published articles on "paper electronics." Paper-based electronics have focused on the fabrication of circuits, supercapacitors, batteries, fuel cells, solar cells, transistors, microwave electronics, digital logic/computation, displays, force-sensing MEMS, user interfaces, optically transparent substrates, substrates with high strength, wearable devices, and biomedical devices based on electrical, biochemical, thermal, fluid, mechanical, magnetic, and photonic interactions. In its natural form, cellulose-based paper is fibrous, renewable, and bendable with the most common forms coming from trees. Paper-like systems use a multi-scale material with millimeter-scale structures built on interlocking micro and nano fibers. This fibrous network permits wicking/handling of liquids for electro-chemo-opto-mechanical sensors.

TRANSFORMATIVE

The new science and engineering knowledge base to be developed will include the following:

1. *Improved understanding, leverage, and prediction of multi-scale behaviors of electrical, photonic, mechanical, thermal, fluidic, magnetic, and chemical properties of fibrous paper-based materials.*
2. *Methods for packaging, preparing, storing, and maintaining reagents and fabricated components on paper-based materials for sensitive and accurate functionality in controlled and extreme environments.*
3. *Fabrication techniques for tunable, scalable, and sustainable production of targeted physical properties and papertronic devices.*
4. *Design rules and descriptions for physical limits of paper as a material for electronic devices.*

A program in papertronics will be transformative with new fundamental science for multi-scale modeling, processing, and functionality of fibrous, paper-based systems. Examples might include advanced understanding for tuned transport of electrical charges and photons in wet and dry porous media and interfaces; pump-less capture of analytes for photonic analysis; tailoring of nano-fibrous morphology for tunable optical devices; processing and sustainable production of paper-based devices; thermal transport to enhance electronic performance; and biochemical and electrical functionalization for sensitive and reliable diagnostic devices. The proposed topic is distinct from current NSF and ENG investments in that there is not a single program that covers the breadth and depth of scientific disciplines required to advance papertronics to a state that will make these technologies viable in addressing national needs.

NATIONAL NEED/GRAND CHALLENGE

These devices with their associated physics and processing are relevant to national needs/grand challenges in environmental sustainability, safety, communication, health, and human performance. Examples might include implantable or wearable devices with predictable degradation or high strength; human-machine user interfaces in controlled or extreme environments; transparent, renewable materials for displays; and disposable computation and sensing for increased situational awareness.

ENGINEERING LEADERSHIP

The Engineering Directorate and NSF sponsored a workshop on papertronics in September of 2016. Based on the registrants' backgrounds, other funding agencies, such as the Air Force, Army, Navy, US Department of Agriculture, NASA, and NIST, along with the private sector and international institutions have the potential to play essential roles in this research initiative. NSF is in a unique position to lead this initiative that will bring academics, future scientists and engineers, and civilians toward fundamental science to realize societal benefits from papertronics.

Appendix

Workshop Support and Participants

Dr. Usha Varshney from NSF Electronics, Photonics, and Magnetic Devices (EPMD) under the Division of Electrical, Communications and Cyber Systems (ECCS) coordinated support from the following divisions of NSF:

Directorate of Engineering (ENG)
- Division of Electrical, Communications and Cyber Systems (ECCS)
- Division of Chemical, Bioengineering, Environmental, and Transport Systems (CBET)
- Division of Civil, Mechanical and Manufacturing Innovation (CMMI)

Directorate of Mathematical and Physical Sciences (MPS)
- Division of Materials Research (DMR)

Directorate of Computer & Information Science & Engineering (CISE)
- Division of Computing and Communications Foundations (CCF)

In addition to NSF, participating government agencies included the US Air Force, the US Department of Agriculture (USDA)/US Forest Service, the National Institute of Standards and Technology (NIST), the Navy, the Army, and the National Aeronautics and Space Administration (NASA).

The non-government participants came from academia and industry with the majority having contributed technological advances to papertronics over the past decade. The names of many of these participants are present in the agenda shown in the previous section. Of these, George Whitesides from Harvard University delivered the keynote address. International contributors included Elvira Fortunato from Universidade Nova de Lisboa (Portugal) and Ronald Österbacka from Åbo Akademi University (Finland). A total of 86 participants registered and attended the workshop.

List of 86 Participants that Registered, Attended, and Participated in the Workshop

Name	Affiliation
Joseph A. Akkara	National Science Foundation
Massood Atashbar	Western Michigan University
Filbert Bartoli	National Science Foundation
Sankar Basu	National Science Foundation
Hans Boehringer	DCN Diagnostics
Tianyi Cai	Ohio University
Jorge Chavez Benavides	Air Force Research Laboratory
Chao-Min Cheng	National Tsing Hua University, Taiwan
Seokheun Choi	Binghamton University
Linda A. Chrisey	Warfighter Protection & Applications Division
Shishir Chundawat	Rutgers University
Bill Compitello	Printed Electronics at Xerox
Khershed Cooper	National Science Foundation
Richard Crooks	The University of Texas at Austin
Frederique Deiss	Indiana University-Purdue University
Madan Dubey	US Army Research Laboratory
Nadia Elmasry	National Science Foundation
Mahmoud Fallahi	National Science Foundation
Elvira Fortunato	Universidade Nova de Lisboa, Portugal
Elain Fu	Oregon State University
George Gamota	Science and Technology Management Associates, LLC
Shubhra Gangopadhyay	University of Missouri - Columbia

Lawrence Goldberg	National Science Foundation
Kenneth Goretta	Air Force Office of Scientific Research
Malancha Gupta	University of Southern California
Bruce Hamilton	National Science Foundation
Mark Heise	Arjowiggins Creative Paper
Chuck Henry	Colorado State University
Heidi Hoffman	SEMI
Liangbing Hu	University of Maryland
Muhammad Mustafa Hussain	KAUST, Saudi Arabia
Shideh Kabiri Ameri	The University of Texas at Austin
Zakya Kafafi	AAAS
Trevor Kalkus	NASA
Shashi P. Karna	Army Research Laboratory, Aberdeen
Savas Kaya	Ohio University
Seongsin (Margaret) Kim	University of Alabama
Catherine Klapperich	Boston University
Song-Charng Kong	National Science Foundation
Teng Li	University of Maryland
Tian Li	University of Maryland
Xiuling Li	University of Illinois
Tongfen Liang	Rutgers University
Barry Lutz	University of Washington
Zhenqiang(Jack) Ma	University of Wisconsin–Madison
Michael Mansfield	MilliporeSigma
Val Marinov	North Dakota State University
Rodrigo Martins	Universidade Nova de Lisboa, Portugal
Aaron Mazzeo	Rutgers University
Anne Mckeown	Rutgers University
Ellis Meng	University of Southern California
World Nieh	U.S. Forest Service
Ronald Oesterbacka	Åbo Akademi University
Lokendra Pal	North Carolina State University
Dimitris Pavlidis	National Science Foundation
Assimina Pelegri	Rutgers University
Robert Pelton	McMaster University
Luis Pereira	Universidade Nova de Lisboa
Melur Ramasubramanian	National Science Foundation
Mihail C. Roco	National Science Foundation
Lynn Rothschild	NASA
Jung-Hun Seo	The State University of New York at Buffalo
Stephaney Shanks	UES, Inc
Robert (Duane) Shelton	WTEC
Shekar Shetty	Paper Diagnostics Inc.
Sergey Shevkoplyas	University of Houston
Sameer Sonkusale	Tufts University
Andrew Steckl	University of Cincinnati
Christina Swanson	Juno Therapeutics
Mary Toney	National Science Foundation
Usha Varshney	National Science Foundation
Sha Wang	University of Maryland
Ian White	University of Maryland
George Whitesides	Harvard University
Jingjin Xie	Rutgers University
Yonggang Yao	University of Maryland
Cunjiang Yu	University of Houston
Mona Zaghloul	National Science Foundation
Marjon Zamani	Boston University
John Zavada	NC State University
Victor Zhirnov	Semiconductor Research Corporation
Hongli Zhu	Northeastern University
Junyong Zhu	Forest Products Laboratory
Babak Ziaie	Purdue University
Xiyue Zou	Rutgers University
Mahmoud Zubaidi	Millipore Sigma

Agenda

Day 1 (Monday Sept. 12th)		
Evening (Ernest Hemingway Salon)	5:30-5:45PM	**Grace Wang (Acting Assistant Director for Engineering, NSF): Welcome**
	5:45 - 7:00 PM	**Welcome Reception & Dinner** **(**Members of Workgroup 1 may eat near front of room in Salon 1; Members of Workgroup 2 may eat near middle of room in Salon 2; Members of Workgroup 3 may eat near the back of the room in Salon 3)
	7:00 - 7:30 PM	**Aaron Mazzeo & Christina Swanson: Outline of objectives & sample presentation**
	7:30 - 8:30 PM	**Breakout into Workgroups** (Workgroup 1 stays in Ernest Hemingway Salon 1;Workgroup 2 stays in Ernest Hemingway Salon 2; Workgroup 3 stays in Ernest Hemingway Salon 3)
Day 2 (Tuesday Sept. 13th)		
Morning (F. Scott Fitzgerald Ballrooms D and E)	7:30 - 8:30 AM	**Breakfast**
	8:30 - 9:00 AM	**Fil Bartoli (NSF ECCS), Usha Varshney (NSF EPMD) & Andrew Steckl: Welcome**
	9:00 - 9:05 AM	**Aaron Mazzeo: Introduction**
	9:05 - 9:55 AM	**George Whitesides (Harvard University): Keynote Address**
	9:55 - 10:15 AM	**Catherine Klapperich (Boston University): Global Health and Diagnostics**
	10:15-10:35 AM	**Teng Li (University of Maryland): Paper Structure and Strength**
	10:35 - 10:50 AM	**Break**
	10:50 - 11:10 AM	**Jack Ma (University of Wisconsin): Paper-based Computation and Digital Logic**
	11:10 - 11:30 AM	**Michael Mansfield (EMD Millipore): Manufacturing of Paper-based Materials**
	11:30 - 11:50 AM	**Aaron Mazzeo (Rutgers University): Sensors and Interfaces**
	11:50 - 12:10 PM	**Liangbing Hu (University of Maryland): Nanocellulose, Optics, and Energy**
	12:10 - 12:30 PM	**Andrew Steckl (University of Cincinnati): Paper-based Diagnostics and Electronics**
Lunch (F. Scott Fitzgerald Ballrooms D and E)	12:30 - 1:20 PM	**Lunch**
Afternoon Session 1 (F. Scott Fitzgerald Ballroom E)	1:20 - 1:40 PM	**Ronald Österbacka (Åbo Akademi University): Paper-based Electronics**
	1:40 - 2:00 PM	**Elvira Fortunato (Universidade Nova de Lisboa): Paper-based Electronics**
	2:00 - 2:20 PM	**Heidi Hoffman (FlexTech): A Model for Technical Innovation**

Day 2 (Tuesday Sept. 13th)		
Afternoon Session 2 (Group 1: Ernest Hemingway Salon 1; Group 2: F. Scott Fitzgerald Ballroom D; Group 3: F. Scott Fitzgerald Ballroom E)	2:20 - 4:00 PM	**Workgroup 1: Electronic devices, packaging, and system architectures** (Chuck Henry, Colorado State; Seokheun Choi, Binghamton; Babak Ziaie, Purdue; Bill Compitello, Xerox; Heidi Hoffman, FlexTech; Val Marinov, N. Dakota State)
		Workgroup 2: Healthcare and the environment (Jorge Chavez Benavides, AFRL; Sameer Sonkusale, Tufts; Ellis Meng, USC; Barry Lutz, Washington; Elain Fu, Oregon State; Richard Crooks, UT-Austin; Ian White, Maryland; Sergey Shevkoplyas, University of Houston; Robert Pelton, McMaster; Shekar Shetty, Paper Diagnostics Inc; Hans Boehringer, DCN Diagnostics; Chao-Min Cheng, NTHU
		Workgroup 3: Physics and processing (Liangbing Hu, Maryland; Junyong Zhu, Forest Labs; Malancha Gupta, USC;Luis Pereira, NOVA;Hongli Zhu, Northeastern University)
Afternoon Session 3 (F. Scott Fitzgerald Ballroom E)	4:00 - 4:45 PM	**Panel on Healthcare and Diagnostics: Workgroup 1 has Q&A with All Participants**
	4:45 - 5:30 PM	**Panel on Physics and Processing: Workgroup 2 has Q&A with All Participants**
	5:30 - 6:15 PM	**Panel on Sensors and Electronics: Workgroup 3 has Q&A with All Participants**
Dinner (F. Scott Fitzgerald Ballroom D)	6:15 - 7:15 PM	**Dinner**
Day 3 (Wednesday Sept. 14th)		
Morning (Group 1: Ernest Hemingway Salon 1 Group 2: F. Scott Fitzgerald Ballroom D Group 3: F. Scott Fitzgerald Ballroom E)	7:30 - 8:30 AM	**Breakfast (F. Scott Fitzgerald Ballrooms D and E)**
	8:30 - 9:30 AM	**Breakout into Workgroups: Create Draft of Findings and Finalize Presentations**
	9:45 - 10:00 AM	**Break (F. Scott Fitzgerald Ballrooms D and E)**
	10:00 - 11:30 AM	**Breakout into Workgroups: Create Draft of Findings and Finalize Presentations**
Lunch	11:30 - 12:30 PM	**Lunch (F. Scott Fitzgerald Ballrooms D and E)**
Afternoon (F. Scott Fitzgerald Ballrooms D and E)	12:30 - 1:00 PM	**Workgroup 1: Presentation of Findings of Workgroup 1**
	1:00 - 1:15 PM	**Discussion Discuss the Findings of Workgroup 1**
	1:15 - 1:45 PM	**Workgroup 2: Presentation of Findings of Workgroup 2**
	1:45 - 2:00 PM	**Discussion Discuss the Findings of Workgroup 2**
	2:00 - 2:30 PM	**Workgroup 3: Presentation of Findings of Workgroup 3**
	2:30 - 2:45 PM	**Discussion Discuss the Findings of Workgroup 3**
	2:45 - 3:00 PM	**Aaron Mazzeo & Andrew Steckl: Concluding Thoughts**
	3:00 PM	**Departure Participants Depart**