1) Current state of the field (materials, devices, modeling) and how far away are we from applications (electronics)?

- **Prototype devices demonstrated** using many 2D materials (graphene high-speed transistors, MoS_2 with high on/off ratio)
- **Need to understand metrics** for good performance beyond state of the art: example is that mobility is not useful at 22nm. F_T is not a good metric if F_{max} is low. What are the figures of merit for new devices being considered?
- **Need to understand the applications** outside logic where 2D materials could play a role – what is the device we want to make? Flexible electronics, optoelectronics? **Performance should be driver.** But need to find the applications where performance will be far superior.
- **Challenges** where state of the art is not advanced:
    - Scaling up to large-areas: far away, especially for high-performance applications. Graphene/SiC is only (possible) example of fab-ready 2D material. We need to know how to manufacture 2D materials over large areas.
    - Contacts (For MoS_2, this is critical issue right now. How to make contacts to atomically-thin layer, small DOS, 3D-2D, van der Waals bonding, top vs. side contacts…). Schottky barriers, understanding and tuning.
    - Atomic-scale control (lateral and vertical); edge state control.
    - Establishing dielectrics on 2D materials.
    - Gate control.
    - Doping and impurity/defect control (best graphite and possibly molybdenite are geologic samples!) Need "MBE-quality" materials.
    - Development of new simulation capabilities specifically tailored for 2D materials and devices, must be coupled to experiments, interdisciplinary teams encouraged
    - **In-situ characterization capabilities…**

2) What is needed in the national science infrastructure to transform the promise of this field to an area of US scientific and technological strength?

• **Inexpensive electronics not seen as an area of future US strength.** Most of industry is overseas. Need to understand where US industry will compete. Performance is key.

• Develop theoretical framework for predictive modeling and analyses…for selecting the most promising 2D materials or combination of materials.

• US does not currently have best materials capability in growth/production of 2D materials, including their precursors. **Urgent need for high quality 2D materials for device development.** Who will develop 2D materials at fab quality? This will spur research and industry interest. Example: DARPA GaN program – supplies university researchers with highest quality GaN for research – similar programs for 2D materials? Can funding agencies incentivize this?

• **Standardized, well-characterized precursor materials (graphite, MoS_2, hBN) and program to share materials.** (An experimental "materials genome project"?)

• Need funding to transfer device prototypes to a technology. Need closer connection to industry/end user of technology so the requirements of technology are known. **Metrics for benchmarking devices are needed.**

• Is there a roadmap for technologies outside ITRS/CMOS? How do we know what is needed that doesn't yet exist? **Need a "wish list" for new technologies.** Get industry input?

[Note: previous three items suggest need for NIST involvement.]

• We need to find out whether there are fundamental scientific issues remaining to be addressed. **Game-changing technologies probably need qualitatively new science**: quantum computing, Majorana fermions, exciton condensates, etc.

• Funding agencies should support fundamental discovery-based research with no particular application in mind. **Culture of panel review does not favor high-risk proposals.**

3) What are the key areas in which knowledge and resources limit the progress of this field which may prevent us from reaching the desired goals?

- **A fundamental materials properties database for 2D materials is needed.**
- **Need better connections across interdisciplinary boundaries** (physics/chemistry/engineering). Funding agencies should incentivize this. Especially cross-boundary education. This is a type of "outreach".
- **Stability of funding in basic science as well as development of novel applications in 2D materials is needed.** Funding cycle should be better synched to graduate student studies duration. "Bandwagon" boom-and-bust cycles not good for science. Need to reward steady progress, not just jumping to the latest thing.
- **Need for mechanism to fund equipment purchase/development for the individual PIs.** (MRI inadequate as it rarely longer funds state-of-the-art individual-PI equipment). Opportunity for NSF to collaborate with DURIP?
- New tools for fundamental characterization of 2D materials, interfaces, junctions etc

4) What lessons can we learn from carbon nanotubes that will help speed up R&D of 2D materials and devices?

• The question might imply we are giving up on CNTs, but steady progress is still being made in CNTs. Lesson is that progress takes time, may not be flashy, and we **need to avoid "bandwagon" boom-and-bust cycles.**

• **Uniformity of material, atomic-scale control over placement remain challenges.**

• **Stacking of 2D multilayers in controlled ways may be critical**

5) How are other countries positioned to carry out research in this area and how did they get there?

• EU will fund graphene research at **EUR$1B over ten years** (Flagship)

• There are **differences in (scientific) culture**: example is that Japan values materials growers.

• **Korea has major industrial funding of 2D materials.** US companies appear to be involved only at level at which they can obtain gov't funding. Why?

• **Other countries have mechanisms for supporting research associates, technicians, early-career researchers directly.**

• Need to identify the **mechanisms by which US R&D funding benefits US industry**: Training of skilled workforce? Development of IP in US?