National Network for Critical Technology Assessment

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Demonstration of Expert Elicitation as a Tool in Critical Technology Assessment

Expert elicitation involves the use of a set of formal methods,[1] informed by insights from modern behavioral social science,[2] in which people with a deep technical understanding of a topic of interest are asked to make both qualitative and quantitative judgments, often in the form of subjective probabilities. The methods were first employed in the mid-1970s as part of the early development of decision analysis. Most of the early applications were in support of decisions being made by private-sector parties. Applications to public-sector decision-making began at the end of that decade. Since then, the method has seen a wide variety of applications.[3]

Designed and applied well, we believe that expert elicitation can play a valuable role in critical technology assessment - providing valuable insight about how a technology may evolve in the future. Its application should be limited to questions about which there are people with true expertise. Even then, it is important to remember that the literature shows that all of us, including experts, are routinely overconfident in our judgments about the future.[4] Expert elicitation is not an alternative to investing in the research that is needed to assess the potential of a technology. What it can do is offer guidance to decision makers who need to make decisions before the results of such research become available.

As a first demonstration of this tool, we designed an elicitation in which we asked experts to provide us with judgments about how Beyond-CMOS technologies may evolve over the coming decade. As of June 2023, we have completed 7 such elicitations with plans to complete up to 10 in the coming weeks pending expert availability. Given the limited number of interviews completed to date all results discussed below are preliminary and intended to demonstrate the potential of this method, less any particular finding on the research questions posed to experts. A copy of the elicitation protocol we developed, after multiple iterations with several experts in the field, can be found here.

Each interview was a one-on-one interview conducted over Zoom with an audio recording made to revisit detailed transcripts as we guided experts through our protocol. We began our interviews by first asking experts whether they agreed with the assessment from industry and academic reviews that it is unlikely any completely new technology will replace CMOS as the basic building block for logic/computing devices over the course of the next ten

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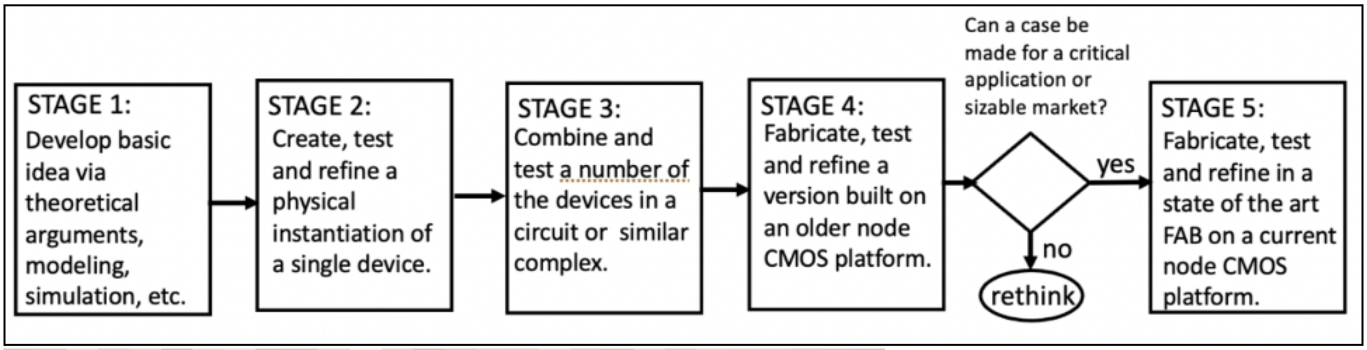
[1] See for example: Morgan, M. G. (2014). Use (and abuse) of expert elicitation in support of decision making for public policy. *Proceedings of the National academy of Sciences*, *111*(20), 7176-7184; Cooke, R.M. (1991). *Experts in Uncertainty: Opinion and Subjective Probability in Science*, Oxford University Press, 336pp; U.S. Environmental Protection Agency (2011). Expert Elicitation Task Force White Paper. Available online at http://www.epa.gov/stpc/pdfs/ee-white-paper-final.pdf

[2] See for example Kahneman, D., & Tversky, A. (1973). On the psychology of prediction. *Psychological review*, *80*(4), 237; Tversky, A., & Kahneman, D. (1974). Judgment under Uncertainty: Heuristics and Biases: Biases in judgments reveal some heuristics of thinking under uncertainty. *Science*, *185*(4157), 1124-1131.

[3] For a summary see "Chapter 9: Expert Elicitation" in Morgan, M. G. (2017). *Theory and practice in policy analysis*. Cambridge University Press, 590pp.

[4] See "Section 9.5 Ubiquitous Overconfidence" in reference 3 above.

years. Across our experts we had broad consensus that there was unlikely to be a drop-in replacement of CMOS over this time frame, but some did posit they thought it plausible a replacement would be commercialized on a timescale longer than a decade.



We then continued by hypothesizing that the development of a new class of semiconductor technology follows a model such as that shown in Figure 1. Here expert feedback was mixed. Many felt it represented an overly simplistic view and offered historical examples of commercialization pathways in the industry that did not follow this process. One participant noted it represented an idealized view of industrial R&D whereas many disruptive innovations can have more circuitous paths to commercialization.

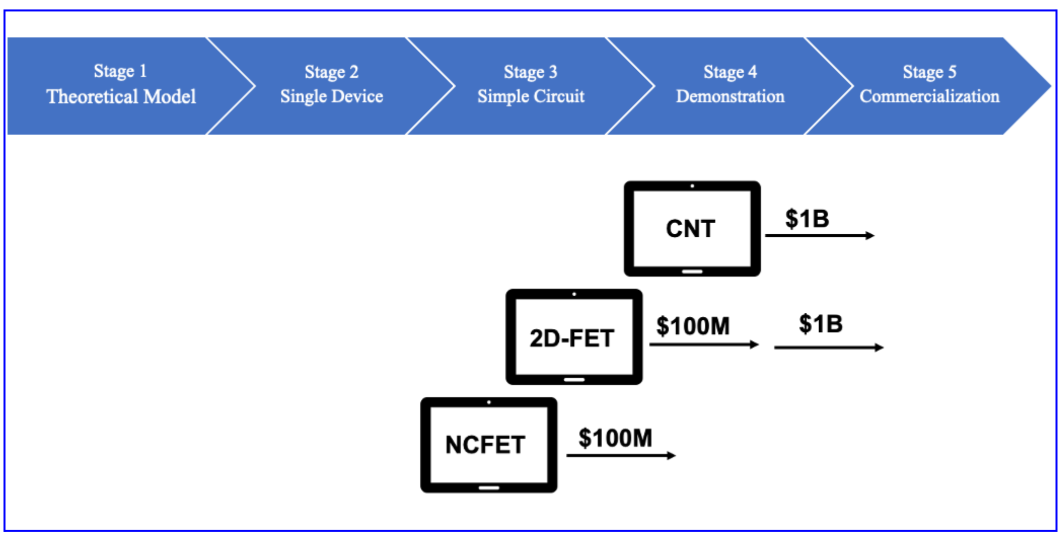


Figure 2 - Summary of expert assessment of certain Beyond CMOS technologies

We provided the expert with a list of a dozen technologies, asked them to choose two or three about which they are most knowledgeable, place each in the appropriate stage of development in Figure 1, and then answer a series of detailed questions about the technology's development, likely future performance, cost, and applications. Given the limited number of completed elicitations we do not have full coverage of each technology but do have feedback from multiple experts on a few candidates: Carbon nanotube FETs, 2D transistors, and the negative capacitance FET. For each of these technologies, experts believed demonstration up to

Stage 4 could be achieved with an investment of O$100M. This level of investment would allow for demonstrating integration with a legacy, or mature, CMOS node and is roughly comparable to a technology readiness level of 5-6. However, experts cautioned that far larger sums would be required to demonstrate commercial viability. Estimates were on O$1B primarily because these technologies each used novel material systems and researchers would need access to 300mm production equipment to properly characterize variability and manufacturing yields.

Experts also had a consensus view on another technology, Tunnel FETs (TFETs). In previous research programs TFETs were considered a leading candidate to replace silicon CMOS[5] because simulations suggested they offered both improved switching speed and more energy efficient operation compared to state-of-the-art CMOS. In the years since, however, experts argued progress had stalled because the improvements demonstrated in practice have been small due to material variability. In short, properly controlling the tunneling phenomenon is expensive to achieve because it requires precise control only possible through complex epitaxial deposition processes.

In disbursing funding from the CHIPS and Science Act to build research portfolios policymakers must grapple with limited funding, a plethora of options and deep scientific and technology uncertainty. This pilot demonstration shows how expert elicitations may be a useful analytical tool in guiding those decisions by leveraging expert insights in a rapidly evolving field.

[5] See discussion in Pan, C., & Naeemi, A. (2017). An expanded benchmarking of beyond-CMOS devices based on Boolean and neuromorphic representative circuits. *IEEE Journal on Exploratory Solid-State Computational Devices and Circuits*, *3*, 101-110