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Semiconductors after Moore's Law: The Economic Benefits of Beyond-CMOS Technology Investments

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1 Executive Summary

Research Issue This article considers the economic value of investments in the technologies that could underpin the next-generation of computing improvement. This question is important because computing is pervasive in our society, generating perhaps a third of national productivity growth and giving a national security edge. Historically, the US led the development and deployment of computing, providing national and competitive advantage. But technical challenges mean that improvements on various dimensions of computing technologies have slowed, putting these sources of advantage at risk. Enormous investments by China also mean that it has largely closed the gap in advanced computing and is now outpacing the US in publications on beyond-CMOS technologies. So, if competitive advantage arises from beyond-CMOS technologies, it may be China rather than the US that benefits. Faced with these realities, it is crucial that computing improvement be re-accelerated and that the US be a leader in developing these technologies.

Developing leadership in beyond-CMOS technologies will require new investments because the traditional method of computing improvement, the miniaturization of CMOS components, is becoming increasingly diffi cult and uneconomical. We are reaching the proverbial "End of Moore's Law." Potential beyond-CMOS successors have been identified, but many are in early stages and will require substantial R&D to develop. This paper analyzes the economic value that these technologies can provide for processors (i.e. not memory) and proposes the portfolio of government investments that would generate the largest expected benefit.

Methods and Data Our analysis proceeds in stages. First, (1) at the macroeconomic level, we estimate the share of economic growth in each sector of the economy that is attributable to semiconductor innovation, and (2) at a microeconomic level, we estimate the economic value to computer buyers of improvements in speed, power, transistor count, etc. We then (3) connect the macro and micro-economic estimates to understand how, historically, improvements in chip performance translated into higher productivity and thus GDP. This allows us to (4) extrapolate the value of particular beyond-CMOS technologies based on their ability to generate chip performance improvements, and (5) calculate the portfolios of investments in beyond-CMOS technologies that - based on various predictions about the likelihood of R&D success - would generate the greatest benefits.

For stage 1, we use sector-level productivity data from US Bureau of Labor Statistics, US patent specifications from the Harvard USPTO Patent Dataset (Suzgun et al. (2022)), and CMOS technology maps from IRDS (2022). For stage 2, we use data on CPU and GPU characteristics for desktop, mobile and server chips from a variety of sources (see Section 4.2 in the full paper). For stages 4 & 5, we use

data on technology characteristics from the IDRS 2022 analysis IRDS (2022) as well as assumptions about how likely these technologies are to be successfully developed. There is substantial uncertainty in both the IDRS projections and our assumptions.

Insight 1: the overall productivity benefit to the economy of improved semiconductors is large We estimate that innovations in semiconductors and hardware design permanently boost productivity by $20B - $40B in the year these innovations are made and by $8b - $16B subsequently, as these improvements are incorporated into other uses. If this were a one-time productivity shock, this would be the extent of the gains. However, because the gains in productivity are permanent, and thus also benefit future years, each year of improvements yields between $600B and $1T in net present economic value for society. Historically, these gains were even larger. If improvements in semiconductors were as fast today as in the heyday of Moore's Law (late 1990s), the gains would be worth an additional $200B-$400B. These calculations highlight the enormous productivity benefits from re-accelerating chip progress (as well as the lost gains to the economy from failing to invest).

Insight 2: we can estimate the gains to the US economy from technical improvements in chip characteristics These imply that the benefits from improvements in chip speed, power, or transistor count are large. As Figure 1 shows, a 100× improvement is worth more than $1 trillion for speed, ~ $100 billion for density, and ~ $400 billion for energy efficiency. And if we get 100× in all three, the benefit is on the order of $10 trillion (because the benefits are mutually reinforcing).

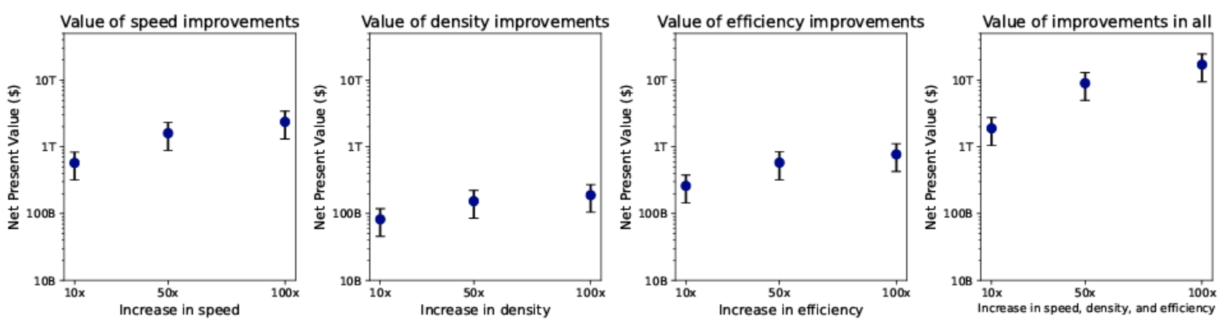

Figure 1: Economic value created for the US economy by 10x, 50x, and 100x improvements in semiconductor speed, density and energy efficiency (relative to CMOS-baseline), as estimated using a hedonic model of chip value.

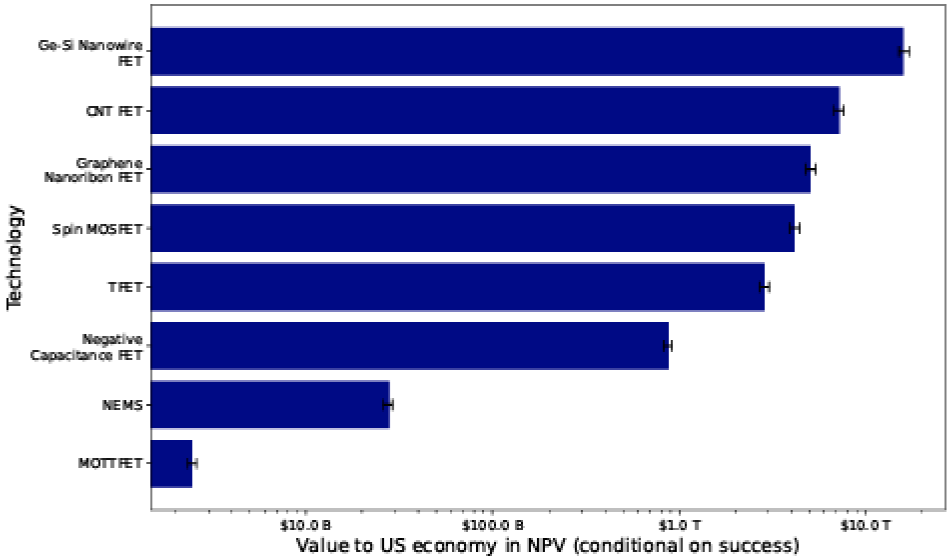

Figure 2: Net present value to the US economy of successfully-developed beyond-CMOS technologies. Based on our economic analysis and technical analysis from the IEEE Roadmap for Devices and Systems. Error bars reflect the uncertainties in the economic analysis, not the uncertainty in Beyond CMOS technology predictions.

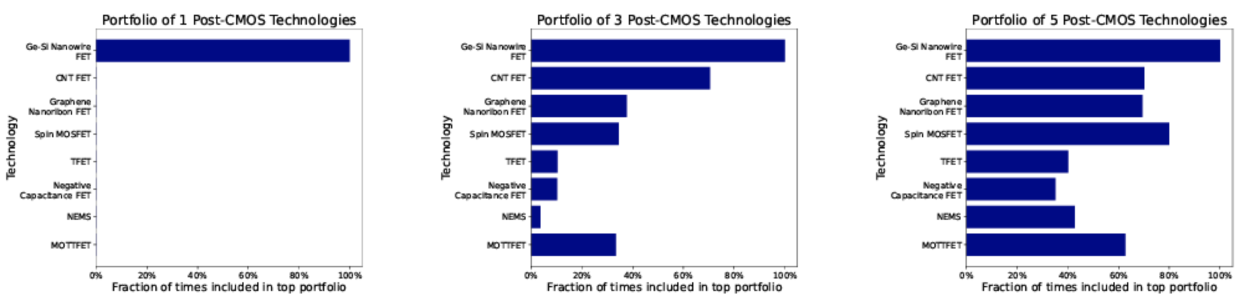

Figure 3: Frequency of beyond-CMOS technologies appearing in optimal portfolio when investing in one, three, or five different technologies simultaneously, based on 3 million simulations per portfolio size.

Applying these benefit estimates to beyond-CMOS technologies yields the expected benefit for the development of each (Figure 2). We then simulate a variety of levels of technology complementarities and probabilities of successful development, to generate investment portfolios of beyond-CMOS technologies (Figure 16).

Insight 3: Early-stage research should be funded well and broadly Our analysis shows that the economic gains from successful development of a beyond-CMOS technologies is often worth over a trillion dollars, some much more. Since the costs of developing these technologies sits disproportionately in later stages of development (e.g. getting to manufacturability), this implies that substantial investments – of tens or hundreds of millions per major technology – should be made for any relatively-promising early-stage technology to maximize the chance of the whole portfolio paying off.

Insight 4: Funding late-stage research is also attractive and all technologies with the reasonable potential for large performance gains should be supported Because the gains from beyond-CMOS are so large, even late stage investments are attractive so long as there is even a moderate likelihood of success. For example, an investment of ten billion dollars would be attractive even if the potential for success was 10% or lower. Moreover, because the cost of getting these technologies even a few years later would cost the economy hundreds of billions, a substantial portfolio of technologies should be funded through late-stage development to maximize the chance of getting these technologies as quickly as possible.