



### A Federal Vision for Future Computing- A Nanotechnology-Inspired Grand Challenge

Collaborating Agencies: Department of Energy (DOE), National Science Foundation (NSF), Department of Defense (DOD), National Institute of Standards and Technology (NIST), Intelligence Community (IC)

#### Introduction

This white paper presents a collective vision from the collaborating Federal agencies of the emerging and innovative solutions needed to realize the Nanotechnology-Inspired Grand Challenge for Future Computing. It describes the technical priorities shared by multiple Federal agencies, highlights the challenges and opportunities associated with these priorities, and presents a guiding vision for the research and development needed to achieve key near-, mid-, and long-term technical goals. By coordinating and collaborating across multiple levels of government, industry, academia, and nonprofit organizations, the nanotechnology and computer science communities can look beyond the decades-old approach to computing based on the von Neumann architecture and chart a new path that will continue the rapid pace of innovation beyond the next decade.

#### Background

On October 20, 2015, the White House announced "A Nanotechnology-Inspired Grand Challenge" to develop transformational computing capabilities by combining innovations in multiple scientific disciplines. The Grand Challenge addresses three Administration priorities--the National Nanotechnology Initiative (NNI), 1 the National Strategic Computing Initiative (NSCI), 2 and the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative 3 to: **Create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain.** 4 While it continues to be a national priority to advance conventional digital computing--which has been the engine of the information technology revolution--current technology falls far short of the human brain in terms of the brain's sensing and problem-solving abilities and its low power consumption. Many experts predict that fundamental physical limitations will prevent transistor technology from ever matching these characteristics.

#### Call for a Coordinated Approach

In the announcement, the White House challenged the nanotechnology and computer science communities to look beyond the decades-old approach to computing based on the von Neumann architecture and chart a new path that will continue the rapid pace of innovation in information technology beyond the next decade. There are growing problems facing the Nation that the new computing capabilities envisioned in this challenge might address, from delivering individualized

1 2

<http://www.nano.gov> <https://www.whitehouse.gov/blog/2015/07/29/advancing-us-leadership-high-performance-computing> 3 <https://www.whitehouse.gov/BRAIN> 4 <http://www.nano.gov/futurecomputing> A Federal Vision for Future Computing: A Nanotechnology-Inspired Grand Challenge treatments for disease, to building more complex and more reliable systems, to allowing advanced robots to work safely alongside people, to **proactively identifying and blocking cyber intrusions.** To meet this challenge, major breakthroughs are needed not only in the basic devices, **computing architecture, and software that store and process information, and in the amount of energy they require, but in the way a computer analyzes information, images, sounds, and patterns; interprets and learns from data; and identifies and solves problems.** Many of these breakthroughs will require new kinds of nanoscale devices and **materials integrated into three-dimensional systems and may take a decade or more to achieve.** These nanotechnology innovations will have to be developed in close coordination with new computer architectures, and will likely be informed by our growing understanding of the brain--a remarkable, fault-tolerant system that consumes less power than an incandescent light bulb.

Comment [i]: **Am an example of what this document is referring to**

Comment [i]: **will be virtually impossible to stop since you would need an AI to access another one the hack of systems will actually become contagious and more destructive and over rides can be more easily accessed since they will all be linked one portal will open all of them**

Comment [i]: **Called AI upgrading itself**

Recent progress in developing novel, low-power methods of sensing and computation—including **neuromorphic, magneto-electronic, and analog systems**—combined with dramatic advances in neuroscience and cognitive sciences, lead us to believe that this ambitious challenge is now within our reach. It is likely that future computing may evolve simultaneously in several directions. Traditional compute intensive and server-based platforms will require continued investment and development. **However, another important direction is the development of computing systems based on constrained power, embedded platforms that are aimed primarily at processing sensor data, providing output and system control.** These systems will extract complex information from massive sensor data streams. In addition, they will learn and improve their capabilities during operation. A successful result of this Grand Challenge may indeed be the identification of application areas (that could be Grand Challenges themselves) that represent new approaches to computing, and then demonstrating the approach's effectiveness through a physical device technology with scalable manufacturing methods, a compatible computer architecture, and demonstrations of applications performance and capabilities. Achieving this Grand Challenge would lead to many game-changing capabilities, addressing the following technology priorities shared by multiple Federal agencies: **Intelligent big data sensors that act autonomously and are programmable via the network for increased flexibility, and that support communication with other networked nodes while maintaining security and avoiding interference with the things being sensed. Machine intelligence** for scientific discovery enabled by rapid extreme-scale data analysis, capable of understanding and making sense of results and thereby accelerating innovation. Online machine learning, including one-shot learning, and new methods and techniques to deal with high-dimensional and unlabeled data sets. Cybersecurity systems that can prevent (or minimize) unauthorized access, identify anomalous behavior, ensure data and software code integrity, and provide contextual analysis for adversary intent or situational awareness; i.e., deter, detect, protect, and adapt. **Technology that enables trusted and secure operation of complex platforms, energy, or weapons systems that require software (or combination of multiple codes) so complicated that it exceeds a human's ability to write and verify the software and its performance.**

2

A Federal Vision for Future Computing: A Nanotechnology-Inspired Grand Challenge · Emerging computing architecture platforms, **neuromorphic or quantum or others, that significantly accelerate algorithm performance, concurrency, and performance execution while maintaining and/or reducing energy consumption by over six orders of magnitude (from megawatts to watts, as achieved by biology)** compared to today's state-of-the-art systems. Indeed, fundamental information theoretic bounds allow such a reduction. **Autonomous or semi-autonomous platforms supporting the observe-orient-decide-act (OODA) process for both military and civilian purposes, such as transportation, medicine, scientific discovery, exploration, and disaster response.**

### Research and Development Focus Areas

The research and development needed to achieve the Grand Challenge can be categorized into the following seven focus areas: 1. 2. 3. 4. 5. 6. 7. Materials Devices and Interconnects Computing Architectures Brain-Inspired Approaches Fabrication/Manufacturing Software, Modeling, and Simulation Applications

These focus areas are discussed in detail below, including near-, mid-, and longer-term goals for each area that will be significant advances in their own right.

#### 1. Materials

**Discovery, understanding, and optimization of novel functional materials, as well as innovative materials integration, are needed for incorporation into advanced devices and architectures.** Specific needs include materials for ultra-low-power digital switches, for interconnects below 10 nm scales, for intrachip optical communication, and for new architectures such as neuromorphic computing, quantum computing, etc. New two-dimensional (2D) materials are attracting considerable research interest due to their potential for nanoelectronic applications. Graphene and other 2D materials (e.g., BN, MoS<sub>2</sub>, WS<sub>2</sub>, and fluorographene) are currently being considered for nanoelectronic logic applications. Individual 2D materials can be arranged into heterostructures with atomic precision, thus creating stacks with novel electronic properties. **Superstructures built from combinations of different 2D materials offer dramatically richer opportunities in terms of physics and transport properties than each of the individual materials.** Since the band structure of 2D materials depends on the number of layers, simply by changing the thickness of one of the components, one can fine tune the resulting electronic and optical properties. An important task for sub-10 nm nanoelectronics is recognition of the fundamental role of "defects" that should

Comment [i]: **The fox running thee hen house**

Comment [i]: **this is incalculably stupid to allow AI to watch over itself --there is no way programmers today can understand the uploading and learning and analysis that AI does and they have admitted this ad now going to hand over the security network of a planet to a system that could deduce that the mankind is the problem and then devise methods and means to exterminate or assimilate the issues the directive is flawed and the directors would have to be brought into question**

Comment [i]: **AI control over everything**

not be treated as imperfections but instead as thermodynamically controllable entities. In fact, thermodynamics dictates the theoretical impossibility of "defect-free" materials of finite size. Due to nonstoichiometric defects, materials often behave as doped semiconductors, and can be described using the classical semiconductor model. A full understanding of nonstoichiometric and doping effects in metal oxides is required in order to control and optimize these and other properties for practical devices. The scaling limits of electron-based devices such as transistors are known to be on the order of A Federal Vision for Future Computing: A Nanotechnology-Inspired Grand Challenge 5 nm due to quantum-mechanical tunneling. Smaller devices can be made if information-bearing particles with mass greater than the mass of an electron are used. **Therefore, new principles for logic and memory devices, scalable to ~1 nm, could be based on "moving atoms" instead of "moving electrons,"** for example, by using **nanoionic structures.** **Examples of solid-state nanoionic devices include memory (ReRAM) and logic (atomic/ionic switches).** A critical issue for any new device material is the ability to achieve control of the properties of "semiconductor" materials that is comparable to that realized in conventional semiconductors. Solid-state systems are, in general, not best suited for moving atoms, **and concepts of fluid nanoelectronics/nanoionics from liquid media may offer a new path to replace the foundation of today's computing technologies.** **Ions in liquid electrolytes play an important role in biological information processors such as the brain or living cells.** Based on this analogy, a binary state could be realized **by a single ion that can be moved to one of two defined positions, separated by a membrane (the barrier) with voltage-controlled conductance.** **Although at an early stage, fluid nanoelectronics could allow for powerful and energy-efficient computing. Fluid nanoelectronics systems could be reconfigurable, with individual elements strung together to create wires and circuits that could be reprogrammed.** Such flexibility would be in distinct contrast to conventional electronic circuits, which are hardwired by a fixed network of interconnects. **Examples include nanoionic devices based on electrolyte-filled nanochannels, and protonic transistors based on ionomers (polymers with ionic properties that may offer a merger of solid-state and fluid nanoionics).** In principle, such structures might be used to make devices scalable to ~1 nm or below. **Such methods and principles also offer the potential for self-healing of nanodevices** and more efficient heat removal. Large-scale computational efforts are needed for understanding and predicting material properties for future information technologies because: (1) **the structures themselves are neither atom-like nor bulklike;** (2) **interfaces modulate device properties;** and (3) **systems operate under non-equilibrium conditions.** A full understanding of the thermodynamics and kinetics of point defects in metal oxides would open the way to precisely engineered semiconductor properties. Development of computational models for tunneling in metal oxides is a critical task, both for the ultimate scaling of transistors and flash memory devices and for new emerging devices. Another example of a mission-critical task is to develop a better physical understanding to enable predictive models for the heat transport properties of semiconductors at the nanoscale. Computational explorations of **emerging two-dimensional (e.g., graphene, BN, MoS<sub>2</sub>, WS<sub>2</sub>, fluorographene), one-dimensional (carbon nanotubes, etc.), and zerodimensional (quantum dot) materials can potentially lead to new insights** and discoveries of new thermal, electronic, and optical phenomena. Accurate first-principle models that address realistic structure sizes and that operate at multiple scales are needed to support further developments in nanoscale information technologies, such as those being addressed by the Materials Genome Initiative. 5 An important attribute of all biological computing systems is the use of inherently three-dimensional (3D) materials and structures. Therefore, methods for 3D nanofabrication are critical for future brain-inspired computing technologies. **Possible directions include 3D lithographic patterning, 3D self-assembly (including programmable, DNA-controlled self-assembly), and inkjet printing. Also, biological 3D nanofabrication may serve as an inspiration for future manufacturing technologies: the living cell is capable of fabricating amazingly complicated structures with high yield and low energy utilization.**

#### **How A Federal Vision for Future Computing:**

A Nanotechnology-Inspired Grand Challenge can an understanding of such **"cellular factories"** be used to guide substantial improvements in the processes now used in semiconductor manufacturing? **It is known that silicon-based memory may become prohibitively expensive for zettascale "big data" deployments in a decade or two.** However, **DNA could be a candidate for scalable, random-access, and error-free information storage. DNA research has demonstrated an information storage density that is several orders of magnitude higher than any other known storage technology.** Potentially, a few tens of kilograms of DNA could meet all of the world's storage needs; moreover, DNA can store information stably at room temperature with zero power requirements, making it a suitable candidate for large-scale archival storage. A new materials base may be needed for future electronic hardware. While most of today's electronics use silicon, this approach is unsustainable if billions of disposable and short-lived sensor nodes are needed **for the coming Internet-of-Things (IoT).** To what extent can the materials base for the implementation of future information technology (IT) components and systems support sustainability through recycling and bio-degradability? **More sustainable materials, such as compostable or biodegradable**

**Comment [i]: the concepts here they are referring to is cellular coommunication~ how th body cells transmit signals ina saline solution ( salt ) and as the conductance of the signals reach the cell the lipid membrane acts as an insulator and regulator to allow the data to flow through it without damaging the synapses**

**Comment [i]: could aborted babies or people who have died have there dna re cycled and then used to implement a data storage or operating system--ORR has this already being utilized in the R & D**

systems (polymers, paper, etc.) that can be recycled or reused, may play an important role. The potential role for such alternative materials in the fabrication of integrated systems needs to be explored as well. 5-year goal: Identify promising emerging materials systems suitable and with high potential for device fabrication and CMOS integration. Concurrently, begin development of the measurement science and technology required to determine materials properties and scaling effects. 10-year goal: Enable physical modeling and simulation at scales that will allow for the characterization, simulation, and prediction of potential device behavior and performance for future circuit designs and analysis. Conduct parallel efforts to address multiple aspects of the materials problem (discovery, characterization, manufacturability), where integration of such efforts will inform the direction of each individual effort. 15-year goal: Achieve a fundamental understanding of materials properties, scaling, and prediction for the properties of new materials systems and their performance and characterization; of their suitability for the design, fabrication, and scalability of new devices; and of their integration with CMOS.

## 2. Devices and Interconnects

In an ongoing Nanotechnology Signature Initiative, Nanoelectronics for 2020 and Beyond, 6 the efficacy of using non-charge-based devices as a replacement for conventional charge-based transistors has been explored. There the goal is to determine if other state variables—electron spin, magnetization, strain, phase, molecular conformation, or yet other physical quantities—could be used as a variable for switching, and thus replace the role of electric quantities (charge, voltage, current) in transistors, and to ultimately determine if significant benefits could be derived from such novel devices. The outcome of this effort has been a gamut of potential non-charge-based devices, including essentially mechanical devices that exhibit switching phenomena, but as yet no single candidate has emerged as an ideal alternative for today's silicon CMOS transistors. The reason could be that while an alternative switch must function at low power levels, for it to be successfully integrated into a computing architecture it

6

National Nanotechnology Initiative Signature Initiative: Nanoelectronics for 2020 and Beyond (National Science and Technology Council, Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology, July 2010: <http://www.nano.gov/NSINanoelectronics>).

5

## A Federal Vision for Future Computing:

A Nanotechnology-Inspired Grand Challenge must also satisfy a large number of other criteria, such as scalability, reliability, crosstalk, manufacturability, and feasibility of integration into a common platform. Current transistors operate at about one volt; with the emergence of millivolt switches the task of organizing and interconnecting them into higher-level functional blocks calls for fundamentally new computer architectures. Besides an overall change in architectural framework involving devices, memory, interconnects, and modes of data transfers between them, new methods of error correction are also needed to reach optimum performance levels. In this respect, fundamental innovations in computing technologies will require that future device research be guided by the feasibility of these new devices being accommodated in newer architectures of the future. The performance of today's advanced digital circuits is highly constrained by the need to limit switching energy dissipation, and many new, more energy-efficient device concepts have been proposed that would greatly reduce this constraint. The fundamental theoretical limit of power dissipation for switching is known as the Landauer limit, measured in bit flips, and it is still approximately five orders of magnitude lower than current technologies. In modern processors, the metal interconnects between the switching devices are known to be a greater source of power dissipation than the switching devices themselves. The recent advent of multicore/many-core architectures and network-on-chip technologies have made it necessary to have efficient intra-chip and inter-chip communication. However, the requirements for power, bandwidth, latency, throughput, and scalability of this new development in turn require innovations from materials to circuits to microarchitectures and even systems, encompassing design tools, smart network topologies, and new parallel algorithms and software. A heterogeneous mix of traditional and novel technologies (and materials) for interconnects needs to be explored. This mix includes conventional technologies such as electronics, 3D stacking, radio frequencies, photonics, and silicon nanophotonics, as well as emerging technologies based on novel materials and devices such as carbon nanotube-based interconnects, terahertz solutions exploiting surface plasmonics, and metamaterials. Current device research is primarily focused on single device demonstration. However, equally important is the task of integrating billions of nanometer-scale devices and interconnects into a computing architecture while assuring the availability of suitable programming models, software, and



**manufacturability**--downstream needs that have not historically been addressed in parallel development of both software and hardware. · 5-year goal: **Fabricate and characterize emerging devices, circuits, and interconnects with promising scalability properties and potential integration with CMOS.** Develop open-sourced device models and simulation techniques, and integrate with open and industry standard circuit design and simulation tools and environments. It will be critical to understand and incorporate reliability fundamentals from the start, considering lifetimes and degradation as soon as promising new materials, devices, interconnects, and architectures are identified. 10-year goal: **Develop standard libraries incorporating nonlinear phenomena and fabrication variations. Develop design and simulation environments suitable for large-scale circuit architectures in both analog and digital domains.** 15-year goal: **Enable device and circuit design, modeling, and simulation environments with the capability of predicting device structure, behavior, and performance based on future computing system requirements.** The ultimate goal is to minimize expert knowledge requirements in

A Federal Vision for Future Computing: A Nanotechnology-Inspired Grand Challenge materials or device physics in order to create and design devices based on new materials systems and circuits driven by desired user properties, behaviors, and applications.

### 3. Computing Architectures

The basic architecture of computers today is essentially the same as those built in the 1940s--the von Neumann architecture--**with separate compute, high-speed memory, and high-density storage components that are electronically interconnected.** However, it is well known that **continued performance increases using this architecture are not feasible in the long term**, with power density constraints being one of the fundamental roadblocks. 7 Further advances in the current approach using multiple cores, chip multiprocessors, and associated architectures are plagued by challenges in software and programming models. Thus, research and development is required in radically new and different computing architectures **involving processors, memory, input-output devices, and how they behave and are interconnected.** Application-specific integrated circuits (ASICs) can provide significant performance improvement for specific tasks compared with programmed general-purpose computers. However, ASICs' relatively high non-recurring engineering and design costs only make them commercially economical for large-volume applications (e.g., mobile computing). The development of domain-specific architectural design principles is one approach currently being used to lower this cost, including accelerator-rich architectures. Such design approaches are not only useful for ASICs, but also **for broader applications areas including biomedical imaging, financial modelling, and DNA sequencing.** Other techniques using 3D integrated circuit technologies, crossbar architectures, microfluidic cooling technologies, and software-hardware codesign principles can be leveraged to optimize future computing architecture performance as well. **Computing architecture design innovations are needed to address the power dissipation challenge in the near future in order to ensure the continued economic growth of the IT industry.** The rise of solid-state, nonvolatile memory devices provides the opportunity to collapse the traditional computer data hierarchy and to store with immediate availability all the data required for computation directly adjacent to the processors. **This is the processing in memory (PIM) approach** to overcoming the von Neumann bottleneck. Other paths, such as approximate, probabilistic, and stochastic computing methods, use a variety of approaches to trade off precision in the result for reducing the time to provide a result, or to relax computational determinism for energy efficiency, or to minimize the data required for computation. Algorithms, architectures, and technologies that are developed for these approaches can **also have significant benefit for brain-inspired approaches by minimizing training data requirements, improving performance, and reducing energy.** Architectural design innovations are needed to sustain the growth of computing performance and tackle power dissipation challenges in the near future. An important research goal will be to architect machines that will leverage ultralow power consumption devices built from new material systems that offer alternatives to CMOS technologies based only on silicon.

7

### 4. Brain-Inspired Approaches

Neuroscience research suggests that the brain is a complex, high-performance computing system with low energy consumption and incredible parallelism. **A highly plastic and flexible organ, the human brain is able to grow new neurons, synapses, and connections to cope with an ever-changing environment.** Energy efficiency, growth, and flexibility occur at all scales, from molecular to cellular, and allow the brain, from early to late stage, **to never stop learning and to act with proactive intelligence in both familiar and novel situations.** Understanding how these mechanisms work and cooperate within and across scales has the potential to offer tremendous technical insights and novel engineering frameworks for materials, devices, and systems seeking to perform efficient and autonomous computing. This research focus area is the most synergistic with the national BRAIN Initiative. However, unlike the BRAIN Initiative, where the goal is to map the network connectivity of the brain, the

Comment [i]: **AI upgrading itself --already been happening**

objective here is to understand the nature, methods, and mechanisms for computation, and how the brain performs some of its tasks. Even within this broad paradigm, one can loosely distinguish between neuromorphic computing and artificial neural network (ANN) approaches. The goal of neuromorphic computing is oriented towards a hardware approach to reverse engineering the computational architecture of the brain. On the other hand, ANNs include algorithmic approaches arising from machine learning, which in turn could leverage advancements and understanding in neuroscience as well as novel cognitive, mathematical, and statistical techniques. Indeed, the ultimate intelligent systems may as well be the result of merging existing ANN (e.g., deep learning) and bio-inspired techniques. High-performance computing (HPC) has traditionally been associated with floating point computations and primarily originated from needs in scientific computing, business, and national security. On the other hand, brain-inspired approaches, while at least as old as modern computing, have traditionally aimed at what might be called pattern recognition applications (e.g., recognition/understanding of speech, images, text, human languages, etc., for which the alternative term, knowledge extraction, is preferred in some circles) and have exploited a different set of tools and techniques. Recently, convergence of these two computing paths has been mandated by the National Strategic Computing Initiative Strategic Plan, 8 which places due emphasis on brain-inspired computing and pattern

#### 5. Fabrication/Manufacturing

The National Strategic Computing Initiative recognizes the importance of support for all aspects of computing, including fabrication. From the NSCI fact sheet of July 29, 2015: Sustaining this capability requires supporting a complete ecosystem of users, vendor companies, software developers, and researchers. The Nation must preserve its leadership role in creating HPC technology and using it across a wide range of applications. 9 Access to advanced nanofabrication capabilities for the research community is key for ensuring ongoing improvements in technology, along with collaborations with industry to transition new fabrication methods to commercial scale. A comprehensive industrial ecosystem built around a nanofabrication paradigm will bridge the gap between one-off experimental fabrication and high-volume manufacturing production, and will shorten the product development cycles. Academic and corporate users, including those from small and medium-sized enterprises, will use the increased accessibility to high-performance nanofabrication capabilities to support the missions of the NNI agencies and to help realize the potential of nanotechnology to benefit society. To maximize the societal impact and commercial potential of nanotechnology, we need a new paradigm for nanofabrication that better matches the diverse needs of emerging nanotechnologies. The natural fault tolerance and stochastic nature of neuromorphic computing or bio-inspired circuitry may allow the implementation of a whole new family of "approximate" manufacturing techniques that cannot be leveraged by existing digital computing structures. . . 5-year goal: Develop tools and fabrication capabilities able to integrate new materials systems, potentially similar to additive manufacturing, at scales relevant to this challenge. 10-year goal: Achieve the ability to prototype new computing architectures incorporating new materials systems and nonlinear phenomena with relatively fast turnaround times (from years to months) compatible with state-of-the-art microelectronics practices.

[https://www.whitehouse.gov/sites/default/files/microsites/ostp/nsci\\_fact\\_sheet.pdf](https://www.whitehouse.gov/sites/default/files/microsites/ostp/nsci_fact_sheet.pdf)

A Federal Vision for Future Computing: A Nanotechnology-Inspired Grand Challenge · 15-year goal: Develop a cost-effective foundry process and design methodology widely accessible to a broad range of research and development groups suitable for both low- and high-volume device fabrication/manufacturing.

6. Software, Modeling, and Simulation It is important to realize that progress in future computing will continue to rely and depend upon further improvements in digital computing systems. It is critical to be able to simulate and emulate at scale any new future computing system, and doing so will require current petascale and near-future exascale systems. Therefore, important research and development should continue and potentially increase on the scalability, portability, usability, verification, and validation of extreme-scale computing architectures that will enable future computing to become a reality. In current HPC systems, parallelism and concurrency have become critically important. Breakthroughs will require a collaborative effort among researchers representing all areas—from services and applications down to the nanoarchitecture and materials level—to research, discover, and build on new concepts, theories, and foundational principles. Approaches to achieving beyond-exascale performance and usability will require new abstract models and algorithms; new programming environments and models; and new hardware architectures, compilers, programming languages, operating systems, and runtime systems; and each must exploit domain- and application-specific knowledge. The development and deployment of new materials, models, algorithms, and hardware architectures is expected to decrease latency and energy consumption by several orders of magnitude in overall system computing

Comment [i]: The deep referring to the bible as the body of water that allows a flow and connection on n integrated pattern

Comment [i]: A Federal Vision for Future Computing: A Nanotechnology-Inspired Grand Challenge recognition or knowledge extraction type applications for enabling inference, prediction, and decision support for big data applications. DOE and NSF have demonstrated significant scientific advancements by investing and supporting HPC resources for open scientific applications. However, it is

Comment [i]: Petascale -- In computing, petascale refers to a computer system capable of reaching performance in excess of one petaflops, i.e. one quadrillion floating

Comment [i]: Exascale computing refers to computing systems capable of at least one exaFLOPS, or a billion billion calculations per second. Such capacity represents a

efficiency. Also, with the present trend for performance improvement, a 50 exaFLOP computer that runs within a 20 MW power envelope could be at the head of the TOP 500 list by 2025.

However, to go above and beyond that performance will require a serious research effort that begins now. New software stacks, compilers, data management, analytics, visualization, programming models, languages and environments, extreme-scale emulation, and user interfaces that leverage the full capabilities of the new computing paradigm are required as well. In particular, several important aspects need to be researched and understood; for example, computational theory, including formal methods, modeling, verification and simulation, and metrics for evaluating "brain-like" systems. • 5-year goal: Create programming and development languages and environments, libraries, solvers, and compilers that **do not require deep knowledge and expertise to use**. Resulting software and solutions must support state-of-the-art and beyond-exascale high-performance computing platforms. 10-year goal: Incorporate nonlinear physical and materials phenomena within modeling and simulation systems capable of design, simulation, and verification of future computing architectures, including accurate prediction of performance. Systems should be capable of application exploration and demonstration at large scales. 15-year goal: Develop software methods and techniques capable of automated discovery and exploration of large, complex parameter spaces from a mathematical, materials, physical, biological, fabrication, or computing architecture point of view.

## 7. Applications

The general vision for computing systems enabled by the Nanotechnology-Inspired Grand Challenge for Future Computing includes the ability to process, analyze, and eventually understand multi-modal sensor data streams and complex workflows. Such systems will be able to learn online and in real time 10 A Federal Vision for Future Computing: A Nanotechnology-Inspired Grand Challenge using unsupervised training and will be able to capture and understand complex data structures. These systems will then also be able to plan and generate complex actions in response to the input data. Some examples of such applications enabling new capabilities include the following: • • Scientific discovery and analysis of very large and complex datasets, including automatic discovery from published literature and experimental research facilities. Information and data integrity assurance enabled by tamper-resistant, self-protecting software codes. **Autonomous robotics and vehicles and intelligent prosthetics integrating motion, vision, sound, planning, and understanding**. Cybersecurity will be an important application area for future computing systems. Security can be considered as a design attribute as well, much like performance or power dissipation. From this perspective, we need systems that adapt quickly to threats, faster than human system administrators can respond to prevent (or minimize) unauthorized access, identify anomalous behavior, and provide contextual analysis for adversarial intent or situational awareness. **Future cybersecurity systems will need to provide analytics for modeling and predicting incidents that will enable us to deter adversaries from attack. Also needed are advanced capabilities for detecting adversarial activity with automated response for protection across a wide range of platforms, including network infrastructure, critical national infrastructure, and emerging Internet of Things and supervisory control and data acquisition (SCADA) platforms**. Real-time fusion of disparate data will enable reasoning about the state of the system and selection of optimal defense actions or system adaptations for anomalous conditions. Dynamic response mechanisms intended to influence adversarial actions or confuse and deceive sophisticated attackers can provide an asymmetric advantage for cyber defense. • 5-year goal: **Achieve autonomous capabilities for routine attack scenarios, utilizing enterprise level computing resources, and human-machine augmented capabilities for sophisticated attack scenarios**. 10-year goal: Achieve autonomous capabilities for sophisticated attack scenarios, utilizing enterprise-level computing resources, with routine attack scenarios resolved with compact and energy-efficient computing resources. 15-year goal: **Achieve fully autonomous capabilities for sophisticated attack scenarios with compact and energy-efficient computing resources**.

## Conclusion

This future computing Grand Challenge offers a great opportunity to advance computing to a new historical level, enabling a new computing paradigm able to deliver human brain-like performance in terms of sensing, problem-solving abilities, and low energy consumption. This exciting opportunity requires new approaches to understand new materials, devices, algorithms, software, and their integration within new computing architectures. Research and development in radically new and different computing architectures involving processors, memory, devices, materials, and the way they are interconnected are required. In summary, a significant and well-coordinated national effort across multiple levels of government, industry, academia, and nonprofit organizations is necessary to achieve success in this very important Grand Challenge.

A Federal Vision for Future Computing: A Nanotechnology-Inspired Grand Challenge

Agency Interests

Comment [i]: **the fox watching the hen house --AI in house security which would be compromised if the system had been penetrated**

The following table outlines the interests of the participating agencies in the seven focus areas outlined above. Software, Modelling, and Simulation x x x x x x x x Fabrication/ Manufacturing Brain-inspired Approaches Devices and Interconnects Computing Architectures Applications Materials NSF DOE DOD NIST IC x x x x x

x x x x x

x x x x x

x x x x x

x x x x x

## Related Agency Activities

### 1. Materials

The Division of Materials Research (DMR) 10 and the Division of Civil, Mechanical, and Manufacturing Innovation (CMMI) 11 at NSF have core programs supporting materials science and materials engineering research. Additional efforts at NSF can be found in the Division of Chemistry (CHE) 12 and in the Division of Electrical, Communications and Cyber Systems (ECCS). 13 The NSF Science and Technology Center (STC) on Integrated Quantum Materials at Harvard, Howard, and MIT 14 is currently working on graphene, topological insulators, and nitrogen vacancy centers in diamond, as well as their integration. Developing materials, techniques, and simulation methods for controlled evolution of quantum mechanical states of multiple to many qubit systems is one of the emphasized topics for the upcoming competition of the Materials Research Science and Engineering Centers in DMR. 15 The competitions in FY 2014 and FY 2015 on Two-Dimensional Atomic-layer Research and Engineering (2-DARE) 16 represented an example of close collaboration between NSF and AFOSR. Basic Energy Sciences (BES) at DOE 17 has core programs supporting extensive materials research related to this Grand Challenge. These programs include, but are not limited to, quantum materials broadly categorized in the areas of superconductivity, magnetism, topological materials, quantum coherence, and low dimensions (0, 1, and 2D). BES supports synthesis, characterization, and theory related to these materials at universities and DOE-supported national laboratories, and has recently sponsored reports

10 11

<http://www.nsf.gov/funding/programs.jsp?org=DMR>  
<http://www.nsf.gov/funding/programs.jsp?org=CMMI> 12  
<http://www.nsf.gov/funding/programs.jsp?org=CHE> 13  
<http://www.nsf.gov/funding/programs.jsp?org=ECCS> 14 <http://ciqm.harvard.edu/> 15  
<http://www.nsf.gov/pubs/2016/nsf16545/nsf16545.htm> 16  
<http://www.nsf.gov/pubs/2015/nsf15502/nsf15502.htm> 17 <http://science.energy.gov/bes/>

A Federal Vision for Future Computing: A Nanotechnology-Inspired Grand Challenge directly impacting materials underpinning the needs for future computing. These reports include the 2015 BES Advisory Committee report, Transformative Opportunities for Discovery Science 18 and Neuromorphic Computing From Materials Research to Systems Architecture Roundtable 19 (cosponsored with the DOE-Advanced Scientific Computing Research program office). In addition, three BES-sponsored Basic Research Needs workshops on (1) quantum materials; (2) synthesis science; and (3) instrumentation science have been completed, with reports forthcoming. BES also collaborates with NSF to support National Academy of Sciences studies on materials, many of which are related to future computing needs. NIST has core programs that support the development of the materials science and engineering foundation for future electronics with measurement science, data, and standards covering a broad range of nanoscale and low-dimensional materials, including carbon nanotubes, graphene and related 2D layers, magnetic materials, thin film oxides, interconnects, dielectrics, superconductors, and organic/molecular semiconductors. These efforts span materials structure fundamentals, fabrication process measurements and control, device reliability, and electrical characterization of devices and circuits. Further, through the Materials Genome Initiative (MGI), 20 NIST is building the materials innovation infrastructure that closely integrates advanced computation, data management, and informatics to enable the discovery and deployment of advanced materials such as those needed for future electronics.

### 2. Devices and Interconnects

Several NSF programs within multiple directorates are currently supporting research in this area. Notable among them are the core programs in the Computing and Communication Foundations (CCF) 21 and ECCS divisions. The NSF STC at the University of California, Berkeley on "Energy Efficient Electronic Systems (E3S)" 22 has supported work on novel materials, quantum tunneling field-effect transistors,



nanoelectromechanical switches, and interconnect research for the last 6 years. Together with the Semiconductor Research Corporation (SRC), NSF has recently announced a joint program on "Energy Efficient Computing: from Devices to Architectures (E2CDA)," 23 which, among other aspects of lowpower computer design, is largely focused on devices and interconnect research as well. ONR is presently supporting graphene research and plans to exploit its superior functionalities to develop electronic, optoelectronic, magnetic, and mechanical devices. NIST has core programs that support this area, including measurements for the development of "superfill" mechanistic models for the metallization of high-aspect-ratio trenches in interconnects and through silicon vias and the characterization of nanoporous low-k dielectric thin films. NIST has performed innovative work on the fundamentals of fabrication processes for reliable interconnects, utilizing the concept of "building in reliability," wherein design of metal deposition processes is informed by measurement of the resulting interconnect microscopic structure and subsequently by performance in service. This approach of establishing a feedback method of improving reliability is based on cyclic ties

18 19

[http://science.energy.gov/~media/bes/besac/pdf/Reports/Challenges\\_at\\_the\\_Frontiers\\_of\\_Matter\\_and\\_Energy\\_rpt.pdf](http://science.energy.gov/~media/bes/besac/pdf/Reports/Challenges_at_the_Frontiers_of_Matter_and_Energy_rpt.pdf) [http://science.energy.gov/~media/bes/pdf/reports/2016/NCFMtSA\\_rpt.pdf](http://science.energy.gov/~media/bes/pdf/reports/2016/NCFMtSA_rpt.pdf) 20  
<https://mgi.nist.gov/> 21 <http://www.nsf.gov/funding/programs.jsp?org=CCF> 22 <https://www.e3s-center.org/> 23 <http://www.nsf.gov/pubs/2016/nsf16526/nsf16526.htm>

A Federal Vision for Future Computing: A Nanotechnology-Inspired Grand Challenge among material processing/resulting material structure/resulting material properties. The approach is extendable to any materials system that may emerge as promising for future interconnect systems. IARPA's Cryogenic Computing Complexity (C3) program 24 is developing materials, device designs, and processes for superconducting computing that could offer an attractive low-power alternative to CMOS with many potential advantages. Josephson junctions, the superconducting switching devices, switch quickly (~1 ps), dissipate little energy per switch (< 10-19 J), and communicate information via small current pulses that propagate over superconducting transmission lines nearly without loss.

### 3. Computing Architectures

The E2CDA program jointly announced by NSF and SRC is intended to support innovative device and architecture research. The NSF core programs in the Computer & Information Science & Engineering (CISE) Directorate 25 have ongoing research in design of circuits, systems, and architectures relevant to future computing needs. Several Defense Advanced Research Projects Agency (DARPA) programs 26 have also focused research on reliability and PIM-type architectures.

### 4. Brain-Inspired Approaches

The DARPA SyNAPSE program 27 is an early example of recent efforts showing the path forward, with the goal to meet certain architecture constraints. The software and hardware partition for brain-inspired architectures could be very different than what exists today. For example, an entire algorithm could be built into the hardware (e.g., in DARPA's UPSIDE program 28), where in a sense, the hardware itself becomes the algorithm, and where sometimes the physics does the computation. Albeit somewhat specialized, such systems could have orders of magnitude energy and/or speed performance improvement over current systems, and yet have some flexibility or "programmability" for domainspecific tasks by virtue of network parameters that are adapted and pre-loaded during training. Industry has recently taken steps in this direction; for example, the IBM TrueNorth is an advanced implementation of a similar idea in silicon CMOS technology. Further experimentation with platforms of this type is needed by researchers to fully exploit their potential. The DOE national laboratories have created spiking neural network models that are running on largescale HPC systems with the potential to significantly enhance scientific discovery on high-dimension and highly connected data sets. They have also developed specialty hardware to accelerate adaptive neural algorithms and improve memory and logic interaction on microprocessors, and have developed the Xyce open-sourced software 29--a SPICE-compatible, high-performance analog circuit simulator capable of solving extremely large circuit problems by supporting large-scale parallel computing platforms. DOE has demonstrated an evolutionary "deep learning" optimization that runs on thousands of graphic processing unit (GPU) processors to find the best configuration of the hyper parameters for a network,

24 25

<https://www.iarpa.gov/index.php/research-programs/c3> <http://nsf.gov/funding/programs.jsp?org=CISE> 26 <http://www.darpa.mil/our-research> 27 <http://www.darpa.mil/program/systems-of-neuromorphic-adaptive-plastic-scalable-electronics> 28 <http://www.darpa.mil/program/unconventional-processing-of-signals-for-intelligent-data-exploitation> 29 <https://xyce.sandia.gov/>

A Federal Vision for Future Computing: A Nanotechnology-Inspired Grand Challenge with the goal of enhancing scientific discovery. DOE researchers are also working with academia to explore new methods on neuromorphic and quantum D-Wave processors. Discovering and creating brain-like algorithms is an important area to be addressed by this Grand Challenge. The development of such algorithms is not a priority of the BRAIN Initiative (or the European Human Brain project), and thus this Grand Challenge can fill an important gap. To this end, the DARPA UPSIDE Program Cortical Processor Study 30 and the IARPA MICrONS program 31 are two current efforts beginning to address the issue. The latter program is directed towards discovering mesoscale, brain-like machine learning algorithms by establishing a dialogue between data science and neuroscience. The Cortical Processor Study is aimed at taking existing neural-inspired techniques and merging them with traditional machine learning to create a new set of algorithms that address a number of perceived limitations in existing machine learning, and then to apply these hybrid algorithms to real-world applications. The Collaborative Research on Computational Neuroscience (CRCNS) program 32 at NSF, a decade-long program that is contributing to the BRAIN Initiative, is fostering transformative research on methods for quantifying and predicting neural and behavioral data in biological systems from cellular to human-level brain function. The Neural and Cognitive Systems (NCS) program 33 at NSF also considers technological innovations in neuroengineering and brain-inspired concepts and designs to inform the development of neuromorphic or neural-inspired chipsets and computing devices. Finally, the recently initiated E2CDA program at NSF, while broadly focused on low-power computing, also entertains brain-like algorithms and their architectural implementation at the nanoscale.

#### 5. Fabrication/Manufacturing

Several efforts within NIST address nanoscale 3D self-organization, defect detection, and critical dimension confirmation for new fabrication and computing paradigms. For example, computational methods are coupled with advanced experimental tools to build predictive design modules for the directed self-assembly of block copolymer thin films to enable the fabrication of ultrasmall patterns needed in future computing nodes. The NIST Center for Nanoscale Science and Technology (CNST) is a user facility that supports the development of nanotechnology by providing industry, academia, and other government agencies access to nanoscale measurement and fabrication methods and tools.

<http://rebootingcomputing.ieee.org/images/files/pdf/RCS4HammerstromThu515.pdf>

<https://www.iarpa.gov/index.php/research-programs/microns> 32

<https://www.nsf.gov/pubs/2015/nsf15595/nsf15595.htm> 33

<http://www.nsf.gov/pubs/2016/nsf16508/nsf16508.htm>

\*\*\*\*\*

## DNA strands to create nanobot computer

### DNA shape changed by scientists to create tiny machines and computers

**Structures can be employed as building blocks to create nanobots and basic computing systems**



**The basic double helix structure of DNA can be changed to create shapes such as 'i-motifs' and 'hairpins'** The shape of DNA can be manipulated to create tiny machines and computers, and scientists have discovered a range of new “triggers” to control this process. **Adding substances like copper and oxygen to molecules of DNA can force it to change its shape** **Creating a range of DNA shapes provides**

scientists with a toolkit they can then use to construct tiny pieces of technology from the building blocks of life. “The structure of DNA is usually assumed to be a double helix – that iconic structure that was first proposed by Watson and Crick in 1953 – but DNA is able to change structure,” Dr Zoe Waller from the University of East Anglia (UEA) told *The Independent*. Dr Waller’s team work on a particular structure called the “i-motif”, a four-stranded, knot-like structure that was identified in living cells for the first time in April. Though alternative DNA structures are thought to have a role in the onset of certain genetic diseases such as diabetes and cancer, the UEA research team was not looking for medical applications. “We know these structures do play a role in gene expression, but that was not the role of this study – DNA can be used as a material in making things,” she explained. DNA has potential as a construction material for a variety of technological applications, from nanobots to DNA-coded computers. As its structure is so different, the i-motif can be used as a switch when paired with regular DNA – with the two different shapes being recognised as either “on” or “off”. This has already been applied in basic nanomachine applications, and work by Dr Waller and her colleagues has expanded the repertoire of switches that can be used in such settings. By adding copper salts to DNA in oxygen-free conditions, they found DNA could be changed into an i-motif shape. This could then be further modified into another shape called a “hairpin” by adding oxygen to the mix. These results were published in the journal *Nucleic Acids Research*. “One of the direct applications is in DNA-based computing,” explained Dr Waller.

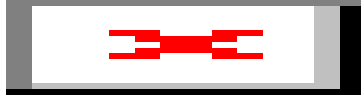
The concept of DNA computing has floated around for years, with Microsoft investigating potential applications and using DNA for data storage. Some scientists have used the code of DNA to store information, or constructed simple logic gates and circuits. “You can use DNA to make logic gates and one of the advantages in using DNA is computing is that you can carry out calculations in parallel if your different types of logic gates are represented by different triggers or ingredients,” said Dr Waller. “So the fact we have discovered separate triggers for the same type of DNA means you could increase the output you could actually use.” Other technological applications of DNA include the creation of tiny “nanobots” that can deliver drugs to parts of the body. “DNA is biocompatible, so if you make a nanomachine out of DNA you can introduce it to a cell and it doesn’t get destroyed or recognised as quickly as some other agents we introduce,” said Dr Waller.

~~~~~

**Researchers use DNA strands to create nanobot computer inside living animal**

April 10, 2014 by Bob Yirka, *Phys.org* [report](#)

Comment [i]: it could execute approximately  $2 \times 10^{19}$  operations per joule (approx.  $10^9$  more than current supercomputers); and utilize memory with an information density of approximately 1 bit per  $\text{nm}^3$  (approx.  $10^8$  more dense than current memory). These advantages mean that it is feasible that a DNA NUTM based computer could potentially utilize more processors than all the electronic computers in the world combined, and so outperform all standard computers on significant practical problems [36].



Atomic force microscope images of robot architectures. Credit: (c) *Nature Nanotechnology* (2014) doi:10.1038/nnano.2014.58

(Phys.org) —A team of researchers at Bar-Ilan University in Israel has successfully **demonstrated an ability to use strands of DNA to create a nanobot computer inside of a living creature**—a cockroach. In their paper published in *Nature Nanotechnology*, the researchers describe how they **created several nanobot structures using strands of DNA, injected them into a living cockroach, then watched as they worked together as a computer to target one of the insects cells.** Prior research has shown that DNA strands can be programmable, mimicking circuits and even solving simple math problems. The team in Israel has now extended that work to show that such **programmability can be used inside of a living organism to perform work** such as destroying cancer cells. DNA strands can be programmed because of their natural tendency to react to different proteins. In this new effort, the team unwound DNA strands and then tied them together in an origami type box structure. The box was then "filled" with a single chemical molecule. Next, other such objects were created for the purpose of interacting with both the box structure and certain proteins found inside of the cockroach. **The whole point was to create multiple scenarios in which the box would open automatically upon colliding with certain proteins.** Adding multiple nanostructures allows for increasing the number of possibilities. For example, if the box structure will only open if it encounters three kinds of proteins, one made naturally by the cockroach, and two others carried by two different DNA origami structures. By mixing the combinations, it's possible to cause the box to open using logic operations such as AND, OR, NOT (where the box will not open if a certain protein is present) etc., and that of course **means that computational operations can be carried out—all inside of a living organism.** In their study, the researchers filled the origami box with a chemical that binds with hemolymph molecules, which are found inside a cockroach's version of a bloodstream. **All of the injected nanobots were imbued with a fluorescent marker so that the researchers could follow their progress inside the cockroach.** They report that their experiments worked as envisioned—**they were able to get the box to open or not, depending on the programming of the entire fleet of nanobots sent into the insect on multiple occasions under a variety of scenarios.** Clearly impressed with their own results, the team suggests that similar nanobot computers could be constructed and be ready for trial in humans in as little as five years.

Comment [i]: **quantum dots**

**Explore further:** [Nanomolecular origami boxes hold big promise for energy storage](#) **More information:** Universal computing by DNA origami robots in a living animal, *Nature Nanotechnology* (2014) [DOI: 10.1038/nnano.2014.58](#)

### Abstract

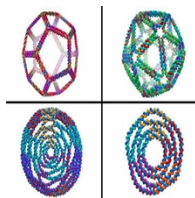
**Biological systems are collections of discrete molecular objects that move around and collide with each other. Cells carry out elaborate processes by precisely controlling these collisions,** but developing artificial machines that can interface with and control such interactions remains a significant challenge. **DNA is a natural substrate for computing and has been used to implement a diverse set of mathematical problems, logic circuits and robotics.** The molecule also interfaces naturally with living systems, and different forms of **DNA-based biocomputing have already been demonstrated.** **Here, we show that DNA origami can be used to fabricate nanoscale robots that are capable of dynamically interacting with each other in a living animal.** The interactions generate logical outputs, which are relayed to switch molecular payloads on or off. As a proof of principle, we use the system to create architectures that emulate various logic gates (AND, OR, XOR, NAND, NOT, CNOT and a half adder). Following an ex vivo prototyping phase, we successfully used the DNA origami robots in living cockroaches (*Blaberus discoidalis*) **to control a molecule that targets their cells.** Read more at: <https://phys.org/news/2014-04-dna-strands-nanobot-animal.html#jCp>

\*\*\*\*\*

### New Computer Model Designs Complicated 3D Structures from DNA

TOPICS: [Biotechnology](#) [DNA](#) [MIT](#) [Nanoscience](#) [Nanotechnology](#)

December 4, 2014



Top row: 3-D structural predictions generated using CanDo by Stavros Gaitanaros, a researcher in MIT's Laboratory for Computational Biology and Biophysics (LCBB),



based on sequence designs provided by Fei Zhang of the Hao Yan Lab at Arizona State University. Bottom row: designs by Keyao Pan (LCBB)/Nature Communications

Biological engineers from MIT have developed a new computer model that enables them to design the most complicated 3D structures ever made from DNA, including rings, bowls, and geometric structures such as icosahedrons that resemble viral particles. This design program could allow researchers to build DNA scaffolds to anchor arrays of proteins and light-sensitive molecules called chromophores that mimic the photosynthetic proteins found in plant cells, or to create new delivery vehicles for drugs or RNA therapies, says Mark Bathe, an associate professor of biological engineering. “The general idea is to spatially organize proteins, chromophores, RNAs, and nanoparticles with nanometer-scale precision using DNA.

The precise nanometer-scale control that we have over 3-D architecture is what is centrally unique in this approach,” says Bathe, the senior author of a [paper describing the new design approach in the December 3 issue of Nature Communications](#).

The paper’s lead authors are postdoc Keyao Pan and former MIT postdoc Do-Nyun Kim, who is now on the faculty at Seoul National University. Other authors of the paper are MIT graduate student Matthew Adendorff and Professor Hao Yan and graduate student Fei Zhang, both of Arizona State University.

### DNA by design

Because DNA is so stable and can easily be programmed by changing its sequence, many scientists see it as a desirable building material for nanoscale structures. Around 2005, scientists began creating tiny two-dimensional structures from DNA using a strategy called DNA origami — the construction of shapes from a DNA “scaffold” strand and smaller “staple” strands that bind to the scaffold. This approach was later translated to three dimensions. Designing these shapes is tedious and time-consuming, and synthesizing and validating them experimentally is expensive and slow, so researchers including Bathe have developed computer models to aid in the design process. In 2011, Bathe and colleagues came up with a program called CanDo that could generate 3-D DNA structures, but it was restricted to a limited class of shapes that had to be built on a rectangular or hexagonal close-packed lattice of DNA bundles. In the new paper, Bathe and colleagues report a computer algorithm that can take sequences of DNA scaffold and staple strands and predict the 3-D structure of arbitrary programmed DNA assemblies. With this model, they can create much more complex structures than were previously possible. The new approach relies on virtually cutting apart sequences of DNA into subcomponents called multi-way junctions, which are the fundamental building blocks of programmed DNA nanostructures. These junctions, which are similar to those that form naturally during DNA replication, consist of two parallel DNA helices in which the strands unwind and “cross over,” binding to a strand of the adjacent DNA helix. After virtually cutting DNA into these smaller sections, Bathe’s program then reassembles them computationally into larger programmed assemblies, such as rings, discs, and spherical containers, all with nanometer-scale dimensions. By programming the

Comment [i]: **The Bull Shit never Ceases-- always about being a benefactor when in reality all they have ever done is weaponize everything**

sequences of these DNA components, designers can also easily create arbitrarily complex architectures, including symmetric cages such as tetrahedrons, octahedrons, and dodecahedrons. “The principal innovation was in recognizing that we can virtually cut these junctions apart only to reassemble them in silico to predict their 3-D structure,” Bathe says. “Predicting their 3-D structure in silico is central to diverse functional applications we’re pursuing, since ultimately **it is 3-D structure that gives rise to function, not DNA sequence alone.**” The new program should enable researchers to design many more structures than those allowed by the CanDo program, says Paul Rothmund, a senior research associate at Caltech who was not part of the research team. “Since a large fraction of the DNA nanotech community is currently using molecules whose structures could not be treated by the original CanDo, the current work is a highly welcome advance,” Rothmund says. The researchers plan to make their algorithm publicly available within the next few months so that other DNA designers can also benefit from it. In the current version of the model, the designer has to come up with the DNA sequence, but Bathe hopes to soon create a version in which the designer can simply give the computer model a specific shape and obtain the sequence that will produce that shape. **This would enable true nanometer-scale 3-D printing, where the “ink” is synthetic DNA.**

### Scaffolds and molds

Once researchers have access to printing 3-D nanoscale DNA objects of arbitrary geometries, they can use them for many different applications by combining them with other kinds of molecules. **“These DNA objects are passive structural scaffolds,” Bathe says. “Their function comes from other molecules attached to them.”**

One type of molecule that Bathe has begun working with is light-harvesting molecules called chromophores, which are a key component of photosynthesis. In living cells, these molecules are arranged on a protein scaffold, but proteins are more difficult to engineer into nanoscale assemblies, so Bathe’s team is trying to mimic the protein scaffold structure with DNA.

Another possible application is designing scaffolds that would allow researchers to mimic bacterial toxin assemblies made from multiple protein subunits. For example, the Shiga toxin consists of five protein subunits arranged in a specific pentameric structure that enables stealthy entry into cells. If researchers could reproduce this structure, they could create a version whose toxic parts are disabled, so that the remainder can be used for delivering drugs and micro- or messenger RNAs.

“This targeting subunit is very effective at getting into cells, and in a way that does not set off a lot of alarms, or result in its degradation by cellular machinery,” Bathe says. “With DNA we can build a scaffold for that entry vehicle part and then attach it to other things — cargo like microRNAs, mRNAs, cancer drugs, and other therapeutics.”

The researchers have also used DNA nanostructures as molds to form tiny particles of gold or other metals. In a recent Science paper, Bathe and colleagues at Harvard

Comment [i]: **combination of nano and dna and the operating system that activates both**

University's Wyss Institute for Biologically Inspired Engineering demonstrated that DNA molds can shape gold and silver into cubes, spheres, and more complex structures, such as Y-shaped particles, with programmed optical properties that can be predicted by computer model. This approach offers a "made-to-order" nanoparticle design and synthesis procedure with diverse applications in nanoscale science and technology.

The current research was funded by the Office of Naval Research and the National Science Foundation.

**Publication:** Keyao Pan, et al., "Lattice-free prediction of three-dimensional structure of programmed DNA assemblies," Nature Communications 5, Article number: 5578; doi:10.1038/ncomms6578

### A DNA computer has a trillion siblings and replicates itself to make a decision



Liquid machines. (Reuters/Mike Segar)

Think of a computer.

You're probably imagining a smartphone or laptop, or even one of Google or Amazon's huge server buildings if you're in the know about [the physical internet](#).

Those modern computers serve us well, but in the future, the word "computer" may conjure images of something much more...squishy. Researchers from the University of **Manchester announced last week that they've taken another step towards building computers from DNA**, a far cry from the silicon processors that underpin our digital infrastructure today. Previous research has shown [these computers are possible](#), but Manchester researchers have built early versions of a theoretical computer called a non-deterministic universal Turing machine (NUTM)—or one that could branch off to explore a series of decisions when given a problem, published in [Journal of the Royal Society Interface](#). To date these machines have only been theoretical, because an infinite and exponential expansion of code would overload even the world's highest-capacity computers. **But DNA is infinitesimal and can self-replicate: a strand of DNA can copy itself an unlimited number of times with slight variations every time it is confronted with a decision—and still fit in a few drops of liquid.**

**Comment [i]: DNA is an excellent medium for information processing and storage [32,33]. It is very stable, as the sequencing of ancient DNA demonstrates. It can also reliably be copied, and many genes have remained virtually unchanged for billions of years. These properties give DNA computing potential advantages in speed, energy efficiency and information storage over electronics [27,28,32,33,35]: the number of operations for a desktop DNA computer could plausibly be approximately  $10^{20}$  s (approx.  $10^3$  times faster than the fastest current supercomputer)**

according to co-author Ross King. The underlying research out of Manchester is complicated, but here are the basics: A strand of DNA is built by arranging [the four chemical bases](#) that make up genetic code into specific sequences. **The DNA is then cycled through 14 parallel chambers containing gene-editing molecules, which prompt the DNA to shuffle itself into trillions and trillions of random combinations.** King offers an analogy: imagine a computer trying to solve a problem is actually trying to navigate a maze. Instead of tracing one path of the maze at a time, **DNA could replicate itself at every junction—and at each point in the maze incorporate new information gleaned from solving the previous step.** **This would let the DNA explore exponentially faster than modern computer processors.** **Each strand of DNA is a processor,** because it's executing the command of **replicating itself with a slight variation, building another processor which can take up its mantle.** Unlike our modern computers which utilize processors that are more or less permanent and can run unlimited kinds of code, these are single-use and disposable, the exact opposite.--The researchers demonstrated the feasibility of this machine in lab conditions, but did not build a complete working NUTM. One problem is the ability to find the code that “solves” the problem (or the right instructions to complete the maze in our analogy). King says the team is working on labels, or easily-detectable markers generated when a solution is found. **This makes it easier for the computer to locate the strands of DNA that are actually useful, which would be floating amidst trillions of similar versions of itself.** Even though DNA sequencing has taken huge leaps since [the late 1970s](#), a machine still wouldn't fit inside your MacBook and probably would take too long to get much work done. Plus, the kinds of pure math problems that NUTMs would solve aren't of much use when browsing Facebook or making spreadsheets. But any research on this front helps us understand how we could use this technology in the far future, whether that means an Amazon server that looks like a gallon of water, liquid data pipelines, or a [computer injected into your head](#).