Healing the Planet: Atomic Precision for Clean Energy & Clean Air

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Table of Contents

About Foresight

The Foresight Institute steers emerging and world-shaping technologies for beneficial purposes and has done so for more than 30 years. It is our mission to spark innovation across multidisciplinary fields such as synthetic biology, artificial intelligence, longevity, and especially nanotechnology. We serve as a nexus for innovation to catalyze research, reward excellence, restrain recklessness, and create community aimed at the long-term flourishing of humanity and the biosphere.

Foreword

We only have one planet (at least, thus far), one place for all of us to live. Yet we are on the verge of destruction of the human home via runaway planetary warming as historical practices of unleashed industrial activities and the individual human activities of our billions push natural processes well past their carrying capacity.

What's a human race to do?

There are efforts to slow the release of carbon that feeds the warming that threatens us all. Even if we achieve a universal political will to make our activities carbon-neutral, the planet will continue heating for hundreds of years.

We must start removing carbon from the atmosphere. We must remove a trillion tons of CO2 over the next 50 years. This is a daunting task, but not impossible.

This workshop designed and proposed several potential solutions and workable projects, focusing on molecular manufacturing to get us there. Some proposals rely, at least in part, on making a profit in order to generate the funding for an altruistic goal of ending what is perhaps the primary existential threat of our time.

A way to sustain a sustainable future.

Atomic Precision for Healing the Planet Workshop

See the video

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Introduction to Scientific Fields Discussed at the Workshop

Growing human population and consumption are increasing demands on the world's environment. Maintaining and restoring the environment in the face of this growth requires effective policies and large-scale affordable technologies. This Foresight workshop examined how atomically-precise manufacturing could create new technologies to help heal the environment on a global scale.

The workshop began with overviews of our environmental challenges and the potential for artificial molecular machines to address these challenges. Small groups then developed ideas for collaborative projects applying these machines to environmental problems. The workshop concluded with presentations and feedback on these proposals.

Presentation 1:
How to Address our Carbon Debt to Heal the Planet

See the video

Tom Chi, founder of GoogleX, described the scale of global environmental problems and what we need to do to address them. He argued that sustainability is not enough. Instead, humanity needs to become a net positive contributor to the environment.

At first sight, the huge scale of humanity's impact on the environment makes it seem that sustainability, let alone a positive contribution, can only occur by a drastic reduction in human consumption. However, this need not be the case. An example arises from comparing human and ant biomass consumption. Each of these groups has similar total mass: 350 million tons. People consume about 3% of their body

mass per day, for a total of 10 million tons of food per day. Ants consume 30% of their mass each day, so their total consumption is ten times larger than that of humans. However, the large consumption by ants is a net positive for the environment because ants provide significant ecosystem services. This shows consumption itself need not be detrimental. Thus drastically reducing consumption is not the only way to address environmental issues.

Moreover, sustainability is not a good target because it depends on technology and market conditions. These conditions change with the development of new production methods and changing consumer preferences. Even if successful, sustainability at best aims for net-zero effect, but this is not enough: if we achieved zero emissions now, the planet will continue heating for hundreds of years. Thus we must aim to make human consumption a net positive for the environment and hence a net negative impact on heating, i.e., we must start reversing the trend rather than merely slowing or stopping it.

Reaching this goal requires approaches with large-scale positive impacts. In particular, we must focus on 'invention catalysts': techniques that are not only better in themselves, but also enable additional inventions. For example, self-driving cars that are not individually owned could have around 40% utilization, compared with current privately-owned cars that are used 4% of the time. This difference means the invention of self-driving cars could lead to significant improvements in city design, e.g., converting much of the land used for parking lots into parks.

We must remove the CO2 already added to atmosphere, not just reduce future emissions. This requires removing a trillion tons over the next 50 years. Tom described three projects, currently under development, that could achieve the necessary scale.

The first project uses drones to plant trees in areas identified from maps as suitable for seeds. This approach can achieve 50% germination rates and is cheaper than conventional planting. The mass of typical commercial trees ranges from 2 to 20 tons, of which 50% is carbon. Planting 20 billion trees/year would require 9000 drones and cost $80M/year to remove about a trillion tons over 50 years. This would require planting an aggregate area comparable to the size of Brazil, e.g., in permafrost. This planting could involve several generations of trees: selecting the type of tree to plant for each area would go through the stages of ecological succession to establish mature forests.

The second project is fully robotic agriculture, to drastically improve efficiency. We currently use about 40% of land surface for agriculture. Automated agriculture could reduce water use by 90%, and use only 1/30th of the land area as now required to grow food. For example, a 2.5 mi^2 farm could feed a city. Moreover, these methods could improve nutrients in soil, as natural plant growth does. This contrasts with conventional farming methods, which reduce soil productivity.

The third project is growing meat from cells rather than animals. Conventional beef production requires 23 calories input to produce one calorie of beef. Cell-based production uses only 3 calories.

Agriculture currently contributes about a quarter of greenhouse gas, comparable to contributions from electricity generation. Thus, improving agricultural productivity can make a substantial contribution to reducing greenhouse gas emissions.

Presentation 2:

Atomic Precision for Clean Energy & Clean Air

See the video

Jonathan Barnes discussed the wide variety of molecular machines researchers have created, and how they compare with such machines assembled and used in nature. A goal of this work is the development of integrated nanomachines, consisting of several kinds of molecular machines with coordinated activity, analogous to the complex molecular machines found in nature.

As one example, DNA provides precise, dense information storage. Molecular machines in cells, such as DNA polymerase, manipulate this information as they duplicate, read, or repair DNA. Other examples are motor proteins that transport cargo along microtubule tracks in cells.

Artificial molecular machines can use mechanical bonds, i.e., linkages, such as found in catenanes or rotaxanes, that are not covalent bonds. These linkages allow a variety of controllable motions in response to light or changes in the chemical environment such as acidity. Laboratory development of molecular machines aims not only to produce controllable functions, but also robust machines capable of many repeated actions before failure. Another use for atomic precision is creating defect-free materials. This would allow materials to approach their theoretical performance limits, e.g., increasing tensile strength by a factor of ten.

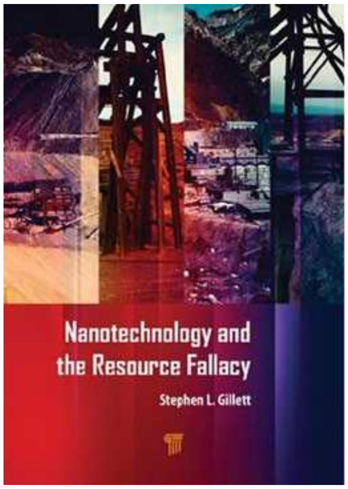
A major challenge for the practical use of artificial molecular machines is scaling up their manufacturing. A recent program at the Department of Energy (DOE) aims to help develop and scale atomically-precise manufacturing and do so with low per-unit cost, analogous to that seen for the cost of individual transistors in integrated circuits. This manufacturing method aims to produce products with essentially every atom in its designed place and with desired bonds to neighboring atoms. This capability will lead to a dramatic increase in our ability to make, manipulate, and react molecules. Funding opportunities such as the DOE program can encourage researchers to design, fabricate, and test molecular machines on larger scales and aim toward practical applications of the machines with better performance than current methods.

An important question for developing molecular machines is whether to focus entirely on artificial molecular machines, or combine them with natural machines from biology. To aid in selecting among these alternatives, we need better characterization of molecular machines, e.g., their heat dissipation, so we can quantitatively compare the performance of new artificial machines with those performing similar functions in biology.

Presentation 3:

Resources, Pollution Control and Nanotechnology

See the video



Steven Gillett, author of Nanotechnology and the Resource Fallacy showed how nanotechnology could improve the environment by creating better filtering technologies. Atomically-precise manufacturing could make molecular-scale filters that precisely separate desired materials from unwanted byproducts and do so with much lower energy use than current methods. Such capabilities could turn the mixture of materials we discard as garbage into economically valuable feedstock for new products. This observation means pollution is a resource in disguise because we currently lack the technology to utilize it.

Current separation methods are very energy intensive, because they use heat for phase separation and require feedstock that is already partially concentrated, i.e., ores. Such high energy use is not fundamentally necessary: more precise technologies could separate materials with energy use closer to the thermodynamic minimum required by the difference in free energy, which is often much less than energy used by current methods. Biology demonstrates low-energy separation, such as in kidneys filtering blood, trees collecting nutrients, and diatoms extracting silicon from seawater.

The difference in energy efficiency of these approaches is analogous to using nonthermal energy generation (e.g., fuel cells) instead of burning fuels to drive heat engines. For example, about 2/3 of the energy in gasoline is lost during combustion instead of doing useful work to move a car. Fuel cells can be more efficient. Plant photosynthesis is another example of efficient energy use. These are examples of the observation that the more spectacular a technology is, the less energy efficient it is likely to be.

To gain this efficiency, we need to mimic nature's molecular approach to move molecules individually, i.e., molecular machines, rather than our current technology that manipulates materials in bulk. For example, ring molecules can separate materials with high selectivity. A challenge for developing artificial molecular separation is that the substrate eventually fills up with the absorbed molecules. We need a way to remove these molecules to regenerate the absorbent. However, the more selective the binding the harder it is to remove the bound molecules. We can overcome this problem by engineering molecular machines to change their binding in response to external changes in their environment, such as molecules that respond to light to change their binding affinity.

Atomic precision can also improve materials by eliminating defects during their manufacture. For example, this could allow replacing metals and cement with carbon for building structures, due to defect-free carbon's much greater strength to weight ratio than metals. While carbon has gained a lot of interest for this reason, it has a disadvantage: it burns. It is also not available in some locations, such as on the moon. An alternative would be to use atomically-precise silicates. Silicates do not burn and are widely available in rocks, including limestone and waste materials from mines. Silicate nanotechnology is not as well developed as carbon-based technology, but laboratory demonstrations show its potential, e.g., creating complex silicate structures in water using organic synthesis methods.

Presentation 4:
Deep Time Perspectives on Climate Change

See the video

Patrick Mellor described several significant climate changes in earth's history, providing context for the scale of changes required to significantly affect climate.

We need to distinguish short-term carbon drawdown and longer-term solutions.

During most of earth's history, atmospheric concentration of CO2 was much higher than it is now, there was no polar ice, and sea levels were 25 to 50m higher. Only about 15% of Earth's history history had extensive ice cover. For instance, the mid-Pliocene, around 5 million years ago, had 350-450ppm of CO2 in the air. In the Eocene, around 50 million years ago, values were 1000-2000ppm, more than twice as high as today's value of 400ppm. This compares with pre-industrial values of 280ppm. CO2 is removed from air either by sequestration and burial, or by dissolving in the oceans. Carbon dioxide added to the ocean increases its acidity, which has detrimental consequences such as preventing shells from forming.

Historically, the large variations in CO2 concentration in the atmosphere arose from massive additions from volcanoes and removal by bioprocesses. This historical perspective illustrates methods we can consider today to have large-scale impact.

For instance, historically, large increases in biomass that fell to the bottom of the ocean without returning carbon to the atmosphere has led to significant cooling. An example is the Azolla event in which algae removed enough carbon to initiate the ice age within a few millennia.

We could repeat the use of biomass for carbon capture over a shorter period of time, by adding iron, which is the limiting nutrient, to the ocean. This occurs to some extent today with iron dust blown into ocean from the Sahara Desert. However, much of the resulting growth rots aerobically when the organisms die, returning the captured carbon to the atmosphere. Thus applying this method to sequester carbon requires careful consideration of locations where the new biomass will sink into anaerobic conditions, thereby capturing the carbon for a long time. Quantitatively, we would need to use the iron from 0.7% of current annual steel production to offset 20% of current CO2 emissions. Moreover, adding iron to the ocean could change its acidity, depending on iron compound used. For example, iron sulfate increases acidity, so it is better to use other iron compounds. This illustrates the need to determine the full range of consequences of geoengineering proposals, not just their effectiveness at carbon capture.

Another approach to address heating from greenhouse gases is to reduce solar radiation on the earth. For example, by using aerosols, similar to the cooling effect of volcano eruptions, or via orbiting mirrors to reflect sunlight away from the Earth. However, while sunlight reduction will reduce temperature, this would not address ocean acidification from increased CO2.

History also has lessons for biological degradation of new materials, such as the problem we face today with plastics. For instance, when trees evolved, around 360 million years ago, lignin in their wood was not digestible. Thus the carbon in dead trees accumulated producing oil reservoirs and leading to an ice age. It took about 50 million years until fungi evolved that could digest lignin. Similarly, we can expect organisms to evolve that digest plastic, which involves simpler chemistry than degrading lignin. This will take a long time to occur naturally, but could be accelerated with biotech.

While history indicates the possibility for long-term carbon sequestration, developing the required technologies at sufficient scale are not current policy priorities. Instead, climate change policy currently focuses on reducing emissions of greenhouse gases. However, merely reducing or stopping new emissions is not sufficient to deal with the heating from aggregate emissions since the start of the industrial era. Thus, current policy diverts attention from developing large-scale sequestration methods.

Presentation 5:
Atomically Precise Digital Matter

See the video

John Randall presented his vision of digital matter to reap the benefits of atomically-precise manufacturing. These include tiny medical robots, such as Rob Freitas' respirocytes, precise pores that can sequence individual DNA molecules, single-atom qubits for quantum computers, bearings that don't wear and defect-free materials close to their theoretical strengths.

These visionary products were one motivation for the National Nanotechnology Initiative (NNI). However, its focus is on miniaturization and simple materials rather than precision. Due to this loss of focus, the NNI has not led to the development of atomically-precise manufacturing. A recent DOE program on atomically-precise manufacturing is a limited step in rectifying this situation.

Manufacturing precision has increased 100,000 times in the last 100 years. We are now close to atomic scale manufacturing, but incremental improvements to current manufacturing technology cannot actually reach atomic precision. Instead, we need a new approach. Digital matter would have a significant possibility of achieving this goal. This idea builds on the existing success of digital electronics in integrated circuits. Using digital rather than analog behaviors allow devices to work accurately in spite of some material variation. Specifically, digital information technology provides immunity to noise and error-free reproduction by check and fix, i.e., using error correcting codes, rather than requiring error-free operation. These advantages allow digital electronics to be much more complex systems than analog.

Digital matter will bring the advantages of digital processes to materials. The main capabilities of this approach are: 1) a binary process of making or breaking chemical bonds; 2) digital addressing of where this process takes place; and 3) error detection and correction, which requires that the process error rate is low enough to correct (or throw out) broken parts, while still giving useful yield. The combination of these capabilities will lead to atomically-precise manufacturing, with essentially all atoms placed and bound in desired structures. These capabilities already exist in biology. For example, the DNA copy process has some errors but cells have error correction to reduce copy errors sufficiently for biological function, i.e., producing the next generation.

Digital matter is possible because physical process have some tolerance for variation. For example, a 10% strain of bond lengths generally relaxes back to the original structure rather than breaking the bonds. The capture distance for bonding is comparable to the bond length, so the strain limit should allow atomically-precise manufacturing with 0.1nm precision for positioning atoms.

Error checking could use a variety of measurable properties of manufactured components. These include the mass and resonant frequencies (mechanical, electrical and optical). Such tests are analogous to using parity check bits for information transmission over a noisy channel.

A key issue for precise manufacturing is how to bridge the several orders of magnitude difference in the size of atomic-scale components and the envisioned products of this technology. One approach is hierarchical assembly, which designs components for precise assembly into larger structures in multiple steps. For example, identical crystals that are atomically precise will merge into a single crystal if placed within the capture distance for bonding. If errors lead to a few extra atoms on the surfaces to be joined, forcing the parts together could push those atoms into the bulk of the material, resulting in a few defects, or push them to the edges of the combined structure. Designing crystals so extra atoms are more likely to move to the edges than into the bulk would reduce the number of defects created by a few errors on surfaces to be joined.

Presentation 6:
Understanding Investment and Fundraising See the video

On Day Two of the workshop, as project ideas began to gel into proposals with the potential to become companies, Tom Chi gave a second presentation; this time on the lifecycle of businesses, the kinds of investment, and the types of investors one may expect and wish to approach.

He began with a short introduction on the stages of how he came to start his current venture fund. Beginning in astrophysics, he moved into engineering, became a tech executive at several noteworthy firms, began to commercialize certain projects, and realized there was an unmet need for how and why investors invest and the type of funding startups should seek - and which to avoid. Upon learning to describe the largely misunderstood subject, he partnered in a new startup fund that is focused on early stage startups.

Stages of Industry

The first subject in his presentation was the Stages of Industry, for which he displayed a schematic graph of the life cycle stages of all industries, which included the Emergent, Growth, Maturity, and Decay stages. Tom states that every single industry goes through these four stages.

At the beginning of the *Emergent stage*, there are no businesses yet in the sector because the concept is moving out of the idea phase and is just beginning to be invented. The idea goes from the not-as-yet-possible, to an idea that may be possible to develop into a commercially viable project or product.

Following this stage is a *Growth stage* that is fairly short, perhaps 1-5 years, where the industry grows dramatically, and the number of companies suddenly increases, to perhaps 20 organizations competing to produce and sell the same type of product.

The third major stage is *Maturity*, wherein the number of companies has fallen off dramatically and a couple of corporations control the great majority of the segment. The Maturity phase may last a decade or possibly several decades.

At some point, demand falls off or is disrupted by a new technological paradigm, and the product, service, or company goes into the fourth stage, *Decay.*

Capital Types and Timing

He went on to show that there are different types of capital that are appropriate to seek or accept with each Stage of Industry.

Grants: The very early Emergent phase is often financed by grants and possibly by Angel investors. It is unknown whether the product or service will become viable, and it is entirely likely that this early funding will see no return.

Debt: Debt may be used for financing at any Stage as long as there is collateral to support a return of something like 10% on the loan.

Venture Capital: VC investment firms are expecting to make ten times their money within three years and such funding is most likely to be appropriate in the Growth stage, including at the beginning of the stage.

Public Shares: Shares in a company are often issued in exchange for funding in the Growth stage in exchange for VC funding, but before an Initial Public Offering.

Private Equity: This type of funding is used during the Maturity and Decay Stages, and may used to buy companies in order to sell off pieces of it and make a profit.

Tom went on to expand on the Emergent Stage, as this is the phase most likely to apply to most of the projects emerging from this workshop.

First comes basic research, as scientists and engineers try to determine if an idea is workable as they invent it. At this stage, there are no competing companies.

The Early Emergent Stage follows once the basic technology is shown to work. At this stage, the founders are determining if it makes sense to move into commercialization of their invention or concept, and there may be one or two competing companies. In the Middle to Late Emergent Stage, the market for the segment begins to develop, and there are more - perhaps 3-10 companies now competing. In the Late Emergent Stage, there are ten or more companies competing, with a shakeout inevitable.

In the Growth phase, one or a couple of companies manage to outperform or acquire the others, taking large swathes of market share, and putting most of the other companies in the segment out of business.

One can figure the stage of a given enterprise by looking to see how many companies are in the space. Based on this determination one can then tell what types of capital to seek.

Cool vs Hot capitalization

Cool capital is patient capital. Often this means angel money, for an angel is in it for the excitement. The angel may not care if they actually make any money on their investment. Small amounts of VC investment may also be cool capital. If the enterprise is on the Emergent spectrum, then it should be interested in cool investment.

VCs are generally investing hot capital. The VC expects to make ten times their money within three years. That would mean, for instance, that to justify $500,000 in VC capital, the company must be worth $5 million three years later. If there are 9 or so competitors in the field, the industry is entering or is about to enter the Growth phase, so that this would be the time capitalize hot.

Understanding Investors

Investors are interested in Allocation, not Valuation - that is, what percentage of the company they own. Below is a table Tom presented that shows the role a given investor may expect based on their ownership / allocation of the company.

Allocation (ownership)	Role
0-4%	Tag / Drag Along – very little input
5-9%	Present at discussions, decisions
10-29%	Governing with other major investors
30-49%	Commanding company decisions
50+%	Owning - making company decisions

Investor Types

Tom discussed the following types of investors, and where their interests generally lie.

- Angels - don't expect to make money – are in it for the excitement.
- Angel list (syndicate) – expect to make some money and have a general manager.
- Corporate (strategic) - invest to stay abreast of or buy into the industry.
- Venture capital
    - Seed fund – first round VC, often invested by incubators
    - Series A/B and Series C/D

These types of investors generally have differing expectations depending upon their level of investment in the company.

Type of Investor	Amount they invest	% ownership they expect	Return expected
Angel	10K-250K	0.1-9%	100x or none
Angel List	100K-1 million	0.5-9%	30x, if any
Seed Fund	100K-1 million	3-10%	30x
Series A Fund	500K-5 million	10-25%	20x
Series B Fund	5-25 million	15-35%	10x
Series C Fund	25-100 million	10-25%	5x
Series D Fund	100 million-1billion	3-10%	3x
Corporate	25K-10 million	Unknown	N/A

Friendly vs Aggressive Investors

Which type of investor one allows or seeks may be a matter of preference. But in general, early stage enterprises will want friendly investors. An aggressive investor may want a greater discount on their investment, more ownership or control, or more seats on the Board than otherwise called for, or special deals in general.

The exception where allowing an aggressive investor in early stages may be appropriate could be if a person really seems to be the perfect partner. But if they are too aggressive, it could spell the doom for the company.

Governance

Startups generally don't fail due to competition. Rather their demise is either from a lack of funding, or from an intractable relationship amongst the founders, investors, or with the Board of Directors or its members. As a result, one will wish to select Board members that know about corporate governance, have applicable expertise, have a long-term orientation, and have adequate bandwidth to pay attention to the enterprise. A potential Board member may seem desirable, but may have their attention split between too many companies.

A Question and Answer session followed Tom's presentation. See the presentation

Needs and Capabilities

To identify areas for collaboration, participants described key bottlenecks for addressing environmental problems and current tools for producing atomically precise materials.

Needs for Environmental Remediation

The most significant bottleneck is the difficulty of scaling up the manufacture of devices to the point where they could have a global impact on the environment. For instance, even if researchers could produce a device to capture carbon dioxide from the air, addressing climate change requires deploying enough of those devices to remove a trillion tons.

Environmental remediation requires inexpensive energy. Lack of adequate materials currently prevents us from achieving this goal. For instance we need materials that can operate at high temperatures to improve efficiency of large-scale power plants, which rely on heat engines to generate energy. Nuclear energy also requires materials resistant to damage from neutrons. Nonthermal energy generation is potentially more efficient than burning fuels to power heat engines. Examples include solar energy and fuel cells. Solar energy requires low-cost materials with high photoelectric efficiency and reliability. Wider use of fuel cells requires better and cheaper catalysts.

In addition to improving energy production, we must use it more efficiently. One area where efficiency could provide huge gains is heating buildings, which currently accounts for a great deal of CO2 emissions. Improving thermal management could reduce this impact, e.g., by developing better heat exchangers and working fluids for heat pumps that could operate at milder temperature ranges than current used.

Addressing a wide range of environmental problems requires better ways to separate, degrade and reuse materials. Examples include methods to break down plastics, remove acid from oceans, and capture CO2 and black carbon particulates. We also need to find effective and benign substitute materials for those currently used that cause environmental damage. For example, much of current green technology relies on rare earth metals, whose production damages the environment.

Soil degradation from agriculture is a major environmental problem. In particular, conventional farming disrupts mycelial networks in soils that distribute nutrients. To remediate soils, we need effective catalysts to recreate and support these nutrient distribution networks, or find effective substitutes for their functions.

Machine learning could potentially identify and evaluate remediation options. Realizing this possibility requires more detailed training data on material capabilities and their environmental impacts.

We need accurate models to evaluate the consequences of large-scale remediation projects, such as removing a trillion tons of CO2 over the next 50 years. In particular, such models could identify detrimental side effects and methods to mitigate them.

In addition to technological bottlenecks, there are important economic and political bottlenecks to effectively using atomically-precise manufacturing to improve the environment.

An important economic question raised at this workshop is how environmentally valuable atomically-precise products are as compared to less precise, but more established approaches, e.g., planting trees. This is particularly important due to the scale of environmental problems and the need to implement remediation technologies quickly. For instance, atomically-precise manufacturing could create higher-performing catalysts to make methanol from biomass. But will this be economically competitive at the scale needed to replace fossil fuels? This contrasts with other motivations for atomically-precise manufacturing, e.g., to produce defect-free materials with much higher strength-to-weight ratios than conventional materials: such new materials will have clear benefit in, for instance, aerospace applications.

A major political challenge is how to create incentives for reducing and removing carbon. Cap-and-trade and carbon taxes are two approaches often discussed. However, while a carbon tax is economically efficient it is politically unpopular. Another political bottleneck is on the use of nuclear energy, which does not release carbon. In particular, thorium-based nuclear reactors have been proposed for decades as more effective approaches than current designs. Geoengineering to reduce the amount of sunlight reaching the earth faces both political and technological challenges.

Capabilities for Precise Manufacturing

An approach to achieving the necessary scale for addressing climate change is exponentially growing manufacturing, in which new production facilities can produce more such facilities. This is analogous to self-replication that occurs in biology, such as the algae growth that sequestered carbon on a massive scale and led to ice ages.

Biochemistry provides some approaches toward atomically precise devices. For example, directed evolution could be targeted toward enzymes that break down plastic. Another use for directed evolution is in creating hierarchical structures, as seen in biological machines, which are macromolecular assemblies, not just one molecule.

Precise genetic modifications through the use of CRISPR could modify trees to accelerate their growth and increase absorbed CO2.

Needs and Capabilities

Scanning probe microscopes can perform atomically precise manufacturing for small numbers of atoms. They can place biomolecules precisely on flat surfaces. Exploiting this tool requires surface scientists to find useful applications, such as designing catalysts that are useful to place with atomic precision on surfaces.

Recent developments show the potential for improved precision. For instance, precise membranes can improve separation of gases or solutes in water, and do so at with much lower energy demands than current separation technologies. New photovoltaic cells that absorb the full spectrum of sunlight improve the efficientcy of solar energy.

In recent years, technology leading to atomic precision has improved significantly. For example, positioning tools now provide Angstrom accuracy over square microns, with open-loop correction of hysteresis of piezoelectric materials in scanning probe microscopes. Holographic positioning can pattern 1-inch wafers with cost below $10/m^2. Although this is not yet atomically precise, this technology may be useful to package atomically precise parts. Faster X-ray diffraction can now generate diffraction pattern of crystals in a few minutes and is amenable to high-throughput applications

Many research groups are developing tools that precisely manipulate molecules. However, the manufacturing capabilities of these tools are not always readily apparent, even to those who create them. Thus an important way to accelerate development of applications of molecular manufacturing is to help application-oriented researchers discover these tools. For example, crowdsourcing could help identify atomically-precise methods already developed in laboratories. Moreover, machine translation could help this process by making foreign language technical publications and patents easily available to others.

Project Proposals

Five teams developed and presented project proposals. A panel of five distinguished judges queried each of the teams after each presentation was made. The panel included :

- Dr. Izik Kizilyalli from the Department of Energy,
- Dr. Daniel Linzer, President and CEO of Research Corporation for Scientific Advancement,
- Dr. Jane Frommer, IBM research Scientist,
- Dr. Jun Axup, Scientific Director & Partner at IndieBio,
- Dr. William Goddard, Charles and Mary Ferkel Professor of Chemistry at CalTech

The judges deliberated at length and selected Heavy Metal Detox of Oceans as the best application of atomic precision for healing the planet.

Additionally, they found Platform Filtration Technology to be the best use of atomic precision, and The Birth of the Carbocene as the most ambitious project.

To aid the development of these proposals, Tom Chi (Co-founder of GoogleX), Daniel Linzer (President of Research Corporation for Science Advancement) and Jun Axup (Scientific Director and Partner at IndieBio) described how to appeal to private funding sources. While the project presentations primarily focused on technical aspects of the projects, they briefly noted possible funding opportunities for the early stages of development.

Project 1: **Heavy Metal Detox of Oceans** See the video

This project will create atomically-precise polymers with binding sites for metals, whose binding affinity varies with stress. Pulling on the polymer releases captured ions into a collection bag that is regularly picked up and replaced. This will allow collecting metals in situ instead of having to return a clogged filter to a lab to remove the collected ions.

These polymers could provide low cost remediation of heavy metals with applications to power plants, oil spills, and mining waste. Scaling up to filtering cubic kilometers of water could help reduce ocean acidification. Early versions of the binding sites would not need to be selective: removing toxic metals would be useful even if the sites also remove other, non-toxic metals. Later versions would be more specific, e.g., by building many variations and screening for selective binding.

The main technical challenge is designing binding sites for metals that release the bound metal when the polymer is stretched. The polymers are robust enough to operate in variable environments found in the ocean. If biofouling is a problem, it will be necessary to functionalize the polymers to reduce fouling.

A commercial issue is the cost of the polymer, which is likely similar to Teflon, with higher cost than most polymers. To compensate for this high cost, the devices must have long operation lifetimes. For example, the proposed polymers could continue to function for over 10,000 cycles.

Project 2: **The Birth of the Carbocene** See the video

Removal of significant amounts of carbon from the air and sequestering it for a long time are important aspects of addressing climate change. Current carbon offset schemes for planting trees focus on removal. But trees return the CO_2 to the atmosphere when they die and then rot. For example, typical trees in commercial forests remove 360 tons CO_2 per acre per year. But 30% of the captured carbon returns to atmosphere when trees die and rot.

This project aims to improve bio-sequestration with large-scale deployment of a biomaterial that extracts carbon from air as it grows, but does not release the carbon when the organism dies. To do so, the project will genetically modify lignin (a component of wood) so it doesn't degrade. The necessary mechanism already exists in some plants, making them resistant to rot. This ability arises from a gene complex. Transferring this complex to fast-growing commercial trees will improve sequestration. The mechanism involves the plant absorbing and using metals, so the modified trees would have the additional benefit of removing metals from the soil, thereby partially remediating contaminated soils.

Confidence in this approach comes from the fact that that massive capture of carbon has happened before. For example, the Azolla event in which algae growth and sequestration deep under water removed enough carbon to initiate the ice age.

The wood from these trees would interest producers of wood-based products including building materials since the modified wood won't rot. This could replace some cement use, which is a major source of greenhouse gas.

Challenges for this approach are the need for mass planting of trees, and developing a transfection method that can maintain the relative positions of multiple genes rather than the common CRISPR technology for placing a single gene. As with other genetic modification projects, this one could face popular objections. This challenge would be at least somewhat reduced by the close connection with environment remediation. Other environmental consequences of massive introduction of modified trees will need careful evaluation.

Project 3: **Platform Filtration Technology**

See the video

Filtering is useful in various remediation applications, such as capturing CO2 from mixtures with other gases, e.g., from power plant exhaust, and collecting nanoplastics in washing machines.

This project will create nearly atomically-precise filtering membranes with a scalable manufacturing technology. Specifically, roll-to-roll manufacturing can produce square meters to square kilometers of membranes. Employing this technology for precise membranes promises an order of magnitude improvement in filtering efficiency compared to conventional membranes.

This project will apply scanning tunneling microscopes (STM) to create precise structures and nanoimprint to create patterns for the membranes. STM provides atomically-precise placement, which is ten times better than e-beam lithography. This technology has already been demonstrated at small scales. For example, Joe Lyding's group has demonstrated the ability to change electronic structure and place molecules at specific places on a silicon surface. Using this capability to write binding sites on a surface will create the pattern. DNA origami can increase the complexity of the patterns. Nanoimprint then transfers the patterns to membranes. This technology can make arbitrary shaped pores, not just circular. This capability allows tuning the filters by varying pore shape in addition to their size.

Using an STM tip to place molecules is precise but very slow. This project will address scalability and need to improve technology for pattern transfer to use with large-scale manufacturing such as roll-to-roll. In particular, researchers have shown how to use micromachines (MEMS) to place millions of such scanners on a wafer. This amount of parallelism is still too slow for consumer products, but sufficient for creating templates for high-value products.

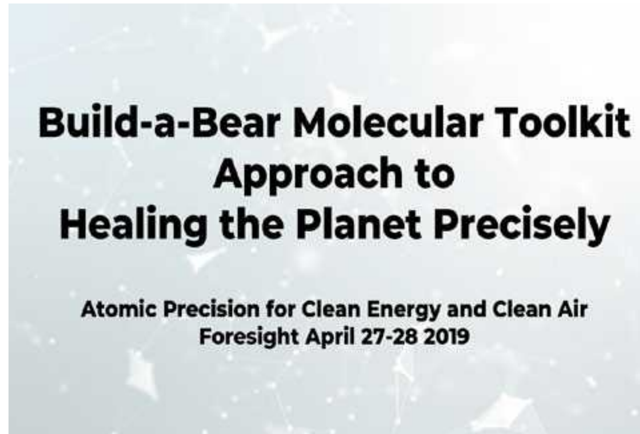
An application of these membranes is to carbon capture by creating pores that capture CO2. This approach to carbon capture will not scale up enough to lower concentration of CO2 by removing it from air. Instead the focus is on point-of-use applications, such as treating the exhaust gases of power plants, which have higher concentrations of CO2, and so is more easily removed than the gas dispersed in air.

Project 4:

Build-a-Bear Molecule Toolkit Approach to Healing the Planet Precisely

See the video

Creating a library of precise products that other companies or researchers could assemble into final products will make the benefits of atomic precision widely available. This project proposal is to create such a library of pores for single-atom layer membranes. This will extend Covalent's commercial development of such membranes for water filtering. Covalent's prior development includes designed surface chemistry, pores and surfaces, and small-scale manufacturing. Covalent expects full-scale manufacturing in three years. This proposal extends Covalent's capability to filtering gases. The design and synthesis of a new pore will take about a year and cost $8 million.



These membranes allow producing liquids or gases with just the desired components by using the same filtering approach as used by kidneys: first remove everything and then reabsorb just the desired materials. This contrasts with conventional filters that remove specified contaminants, requiring redesign to handle additional contaminants. Thus this project will become a precise pore manufacturing shop for licensees, who specify what they want in the membrane's product. The designed membrane filters will reabsorb just those specified components. In this business model, customers receive an exclusive license to use these pores in a broad market segment. An example for water filtering is the company AguaVia. This project will offer similar arrangements for the new gas filtering pores developed by this project.

Project 5: **CarbonAct**

See the video

Providing economic incentives to address environmental problems could encourage development and application of new technologies to these problems. This project is one such example: developing technology to convert CO2 into valuable products. This will provide commercial incentives to sequester the carbon in products with long-term uses.

Potential products include new carbon nanomaterials and high-value chemicals used in the production of pharmaceuticals. For example, graphene is currently worth $1000/kg. Atomically-precise manufacturing could produce defect-free materials, giving much higher strength to weight ratios than today's structural materials. Such materials would be especially useful in aerospace applications.

Production capacity can increase from 1g/day after the first year of the project, to 1000kg/day in 8 years. This level of production will generate significant revenues from high-value products. Once there is a commercially profitable industry in specialized high-value markets, this approach could scale up to remove more CO2. Markets for these products are not likely to support large enough carbon capture to meaningfully contribute to the 50Gt/yr removal rate required to extract the trillion or more tons in 20 years necessary for addressing climate change. Nevertheless, markets for high-value carbon products could contribute toward this goal, e.g., extracting 15 gigatons (Gt) of CO2 from the air per year, using energy from renewable sources.

A significant challenge for creating commercial incentives to sequester carbon is the lower costs of creating the same high-value carbon products from conventional carbon sources (e.g., oil) rather than incurring the additional cost of extracting carbon from a low concentration source (air). Policy changes, such as carbon taxes, could address this by making conventional sources less attractive over the longer term.

Conclusion

The five projects proposed at the workshop are some possibilities for applying atomically precise devices to improve the environment. These projects focus mainly on carbon capture and filtering. Another important benefit of atomic precision is reducing or eliminating waste byproducts by only producing the intended product.

How to scale laboratory demonstrations large enough to significantly improve the environment was an underlying theme of the workshop. Recent decades have shown exponential improvement in capability and unit cost reduction for computation and acquiring biological data. These examples contrast with the linear view emphasized at this workshop, e.g., removing a trillion tons of CO2 over 50 years by removing 20 billion per year starting now. One reason for this focus is that exponentials are much easier for situations involving small amounts of physical material, e.g., faster computing or improved gene sequencing. It is much more difficult to maintain exponentially growing processes that must move and process large numbers of atoms as needed for CO2 reduction. Nevertheless, there are examples of global-scale consequences from exponential biological processes, such as the Azolla algae bloom.

The discussions at this workshop showed that scaling is a much more important theme for addressing global environmental problems than other applications for atomically-precise manufacturing considered at prior workshops. Biology demonstrates that molecular machines are capable of efficient and effective operation on chemicals. As discussed in prior workshops, it is already challenging to scale the manufacture of artificial molecular machines from laboratory demonstrations to commercial scale production. Environmental challenges require even larger production scales to significantly help heal the planet.

Foresight is currently in discussion with members of teams to find ways to successfully manifest some of the proposed projects.

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