ALCOR LIFE EXTENSION FOUNDATION

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ALCOR SCIENTIFIC ADVISORY BOARD MEETING

By Ralph C. Merkle, Chairman, Alcor Scientific Advisory Board

The Alcor Scientific Advisory Board (SAB) met on December 9th and 10th, 2008 in Melbourne, Florida.

The first day was devoted to how the cryonics community could help speed the development of MNT (molecular nanotechnology), and how MNT could enable repair of cryopreserved patients.

Ralph Merkle and Robert Freitas gave a 90 slide Power Point presentation about their plan to develop MNT. Further information about their work is available at The Nanofactory Collaboration website – see http://www.MolecularAssembler.com/Nanofactory, which provides an overview of the issues involved in developing nanofactories.

Part of their presentation discussed a specific set of nine molecular tools composed of hydrogen, carbon, and germanium. This is described in complete technical detail in *A Minimal Toolset for Positional Diamond Mechanosynthesis* – see http://www.MolecularAssembler.com/Papers/MinToolset.pdf. The nine tools can be used to both recharge all nine tools and make additional tools, as well as build a wide range of atomically precise hydrocarbon structures (diamond, nanotubes, polyynes, fullerenes, and many others) – starting from just raw materials (feedstock molecules). The bulk of the paper describes the specific mechanosynthetic reactions required in this process, and their evaluation using Gaussian, a standard computational chemistry package.

They also mentioned the $3M 5-year grant to Professor Philip Moriarty in the School of Physics at the University of Nottingham to experimentally investigate some of the proposed tools and reactions – see http://www.MolecularAssembler.com/Nanofactory/Media/PressReleaseAug08.htm

The Alcor SAB then discussed *The importance of MNT to the cryonics community* and *A cryopreservation revival scenario using MNT* (which both appear in this issue of Cryonics).

Following this, a draft statement of support for research in MNT by the cryonics community was presented. After some discussion and wordsmithing the Alcor SAB formally voted to support this *Endorsement of Molecular Nanotechnology Research and Development* (see the full text in the box below). The full Alcor Board endorsed the statement at their next regular meeting. We plan to seek broader support for this statement.

We'd like to thank all the attendees for making it a stimulating and productive meeting. We'd like to offer our particular thanks to Martine Rothblatt, whose generous support made the meeting possible.

The first day SAB attendees were: Antonei Csoka, Aubrey de Grey, Robert Freitas, James Lewis, Ralph Merkle, Marvin Minsky, and Martine Rothblatt. Non SAB attendees were Gloria Rudisch (Marvin's wife), Lori Rhodes, and Tanya Jones. Martine Rothblatt proposed that the SAB needed a chairman and nominated Ralph Merkle for the position. The nomination was approved unanimously.

On the second day, Melody Maxim joined the discussion, and Martine Rothblatt did not attend (she was at a Terasem meeting). The second day was focused on cryopreservation methods, how they could be improved, and how the credibility of cryonics could be improved in the scientific community. ■

Endorsement of Molecular Nanotechnology Research and Development

The development of molecular nanotechnology will speed solutions to the most difficult problems of medicine, including aging and reversible suspended animation. Molecular nanotechnology is the most compelling approach ever put forward for comprehensive repair of cryopreservation injury with maximum retention of original biological information. Support for immediate development of molecular nanotechnology by cryonicists and life extensionists could compress the historical timeline of this technology, bringing benefits decades sooner than otherwise.

The Importance of MNT to the Cryonics Community

By Ralph C. Merkle and Robert A. Freitas Jr.

A Call To Action

The cryonics community should robustly support research in two critical areas: better methods of cryopreservation, and methods of reviving cryopreserved patients. We already know we must do the former. But now, it seems, we must also do the latter.

The best approach for revival is to develop and apply MNT (molecular nanotechnology). The faster we do this, the sooner we will be able to revive cryopreserved patients and the less time they will spend in storage. We will also obtain medical nanodevices able to cure a wide range of other severe injuries, along with the broader capabilities of MNT that will benefit both us and the rest of humanity.

Look around the world and ask: who has the vision and the will to develop MNT? Few are heeding the call. The development of MNT might be delayed by many decades for want of relatively modest research funding today. To correct this situation we must look to ourselves. We must vigorously fund MNT research now.

Two Key Goals for Cryonics Research

Alcor is a coalition of individuals with diverse beliefs, opinions and hopes. We all share a common belief that life is good, that saving lives is the right thing to do, and that we can save lives through cryonics. We want to save our own lives, the lives of our loved ones, the lives of our friends, the lives of our neighbors, and indeed the lives of everyone we can.

The core of cryonics is easy to describe: those who have exhausted all other medical options can be cryopreserved until future technology can restore them to full and vibrant health.

As a consequence, we (cryonicists as a community) have worked hard to improve our ability to do cryopreservations. Whether by research on better methods, or better facilities, or better equipment, or better training, or better logistics and deployment, we understand that we are the ones who must do the work because there is no one else to do it for us.

This quest for better cryopreservations continues today, and will continue until some future day when fully reversible cryopreservation becomes possible. This is a key goal of cryonics research.

But until that future day arrives, a cryopreserved patient must rely upon the development and the application of new technologies to allow the person's body to be restored to complete health. This is a second key goal of cryonics research.

One of these new technologies is MNT. While in theory there might be other ways to revive cryopreserved patients, MNT is by far the best studied and best known approach. Based on our current knowledge, MNT seems the most likely to give us the vibrant good health that we seek.

Reviving Cryopreserved Patients using MNT

Perhaps the most generally appealing approach to patient revival is to repair the cryopreserved biological structure, returning the person to full health by employing a process that saves and restores the original tissue.* This is technically challenging but appears quite feasible using MNT. One such MNT-based revival scenario is outlined in the accompanying article.

Alternative methods for revival of a cryopreserved patient without direct tissue repair have been proposed, but these too most likely require MNT. The simplest such method relies on the argument that recovery of personality-relevant information is all that is needed. This data could be obtained via high-resolution imaging of the cryopreserved human brain (possibly destructively), after which the resulting information would be used to create an artificial brain with the same memories, hopes, dreams and personality as the person who was cryopreserved. Many people trained in the fields of artificial intelligence, computer science, and philosophy of mind strongly support this option, but some others are uncomfortable with the idea.

Our Community Can Speed the Development of MNT

Can we really make a difference in the development of MNT? The answer is an unequivocal "Yes!" Recent work (see www.MolecularAssembler.com/Nanofactory) makes it clear that the MNT revolution can be accelerated by decades with well focused research investments of only millions to tens of millions of dollars. We have those resources within our community.

Are others working towards this goal? Remarkably, the answer is "No." As first proposed, the National Nanotechnology Initiative had funding to investigate MNT. This funding was removed from the bill under political pressure before it was signed by President Bush in December 2003. Today, funding in the United States for MNT is still being actively blocked and research scientists eager for tenure and grants are careful to avoid the subject. As a result, vital research is not being pursued, advances are not being made, and it is unclear how long this political logjam will continue to block progress. Similar political problems in other fields have often cost decades of delay. In the case of MNT, delay will cost many lives – possibly including ours.

What should we do? We must recognize, once again, that it falls to us to support the

research upon which our lives depend. In this case, we must identify and support the critical research that will speed the development of MNT. As it happens, we have within our community some of the finest minds in the world in MNT (just as we have some of the finest minds in cryobiology, life extension and other areas – which is not an accident).

More specifically, the most direct path to MNT is to develop mechanosynthesis (www.MolecularAssembler.com/Nanofactory/DMS.htm) and then to use it to build the first engineered molecular machines. The Nanofactory Collaboration initiated the first work on the direct path to MNT by publishing an extensive theoretical analysis of early steps in the R&D process. We were then fortunate to persuade Philip Moriarty, one of the finest experimentalists in the United Kingdom, to join us in realizing the first step along this path. In late 2008, Philip received a 5-year $3 million grant from the Engineering and Physical Sciences Research Council to experimentally investigate the Collaboration's mechanosynthesis proposals (see www.MolecularAssembler.com/Nanofactory/Media/PressReleaseAug08.htm). This grant was historic but, sadly, unique. Additional funding from traditional mainstream sources in the United States or elsewhere appears unlikely anytime soon.

What is MNT?

Molecular nanotechnology is the anticipated future ability to manufacture products by inexpensively arranging atoms in most of the ways permitted by physical law. The idea was first discussed in Richard Feynman's visionary 1959 talk "There's Plenty of Room at the Bottom." Since then, Feynman's original intuition has been supported by a wealth of both experimental and theoretical research.

On the experimental front, it is almost routine to arrange tens to hundreds of atoms in atomically precise patterns on various atomically flat surfaces, spelling out corporate or governmental logos, or arranging atoms in patterns useful for some limited scientific purpose.

On the theoretical front, computational analyses fully support the idea that molecular tools should be able to hold, position and assemble molecular parts into complex three dimensional structures. Experimental work to explore these possibilities has begun, and dramatic results are expected over the coming years and decades.

The ability of molecular manufacturing machines to build more molecular manufacturing machines should lead to many orders-of-magnitude price reductions for both the machines themselves and the products that those machines can manufacture. A readily accessible example of such a capability can be found in nature: potatoes can make more potatoes, and as a consequence potatoes are widely available at low cost. When examined closely, the potato is made of exceedingly complex molecular machines able to build more molecular machines – yet we think nothing of mashing these miracles of nature and, with a little butter and salt, eating them for dinner.

MNT should bring the economics of potatoes to a much wider range of complex atomically precise manufactured products, including products made from diamond, graphene, fullerenes, carbon nanotubes, sapphire, and a host of other astonishingly strong and lightweight materials. This capability will let us inexpensively build remarkably powerful computers and vast fleets of medical nanorobots that can directly intervene in biological systems even at the level of cellular, subcellular, and molecular structures. Armed with these nanodevices, doctors will be able to repair even extensive damage to human tissues. MNT will revolutionize medicine, marking a quantum leap in our ability to stay healthy and thus to avoid much of the need for cryopreservation in the first place. Developed in time, MNT could play a role in the demonstration of fully reversible cryopreservation.

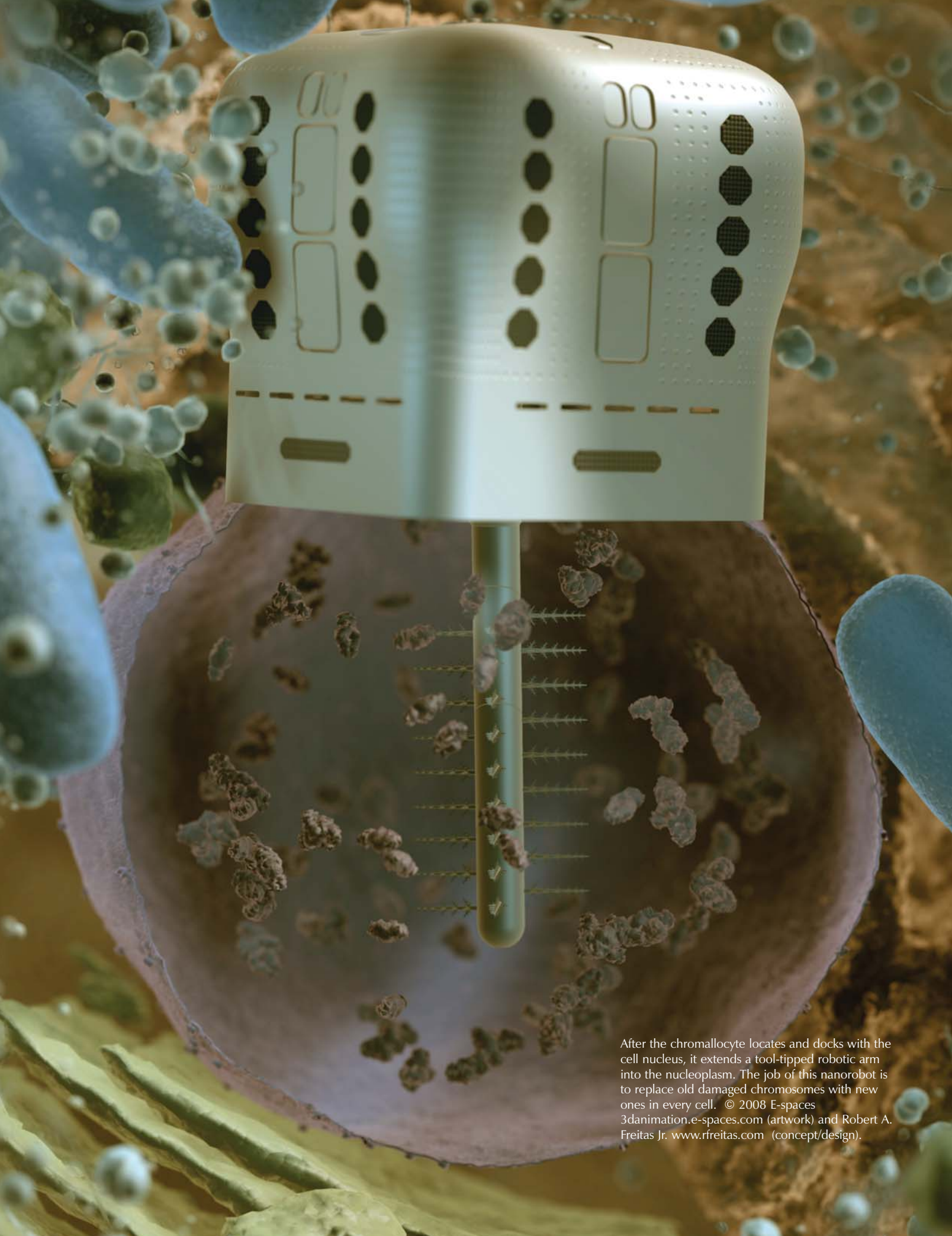
More generally, MNT is expected to provide material abundance for humanity and enable a whole range of novel capabilities beyond better computers and medical technologies – such as the ability to feed a hungry world, roll back environmental damage, directly control the climate, and afford cheap access to space. MNT gives us options for improving the human condition that can scarcely be imagined today.

As with many other technology revolutions in the past, MNT will open up major new avenues for wealth creation beyond life preservation, likely producing a fresh crop of global billionaires among those few farsighted individuals who grasp the opportunity.

Acknowledgements

We would like to thank Aubrey de Grey and Brian Wowk for their comments and insight on an earlier draft which greatly improved the final result. ■

* Published literature on revival includes: Robert C.W. Ettinger, **The Prospect of Immortality**, Doubleday, NY, 1964; Jerome B. White, "Viral Induced Repair of Damaged Neurons with Preservation of Long-Term Information Content," **Second Annual Cryonics Conference**, Ann Arbor MI, 11 April 1969; Michael G. Darwin, "The Anabolocyte: A Biological Approach to Repairing Cryoinjury," **Life Extension Magazine** (July-August 1977):80-83, http://www.alcor.org/Library/pdfs/anabolocyte.pdf; Thomas Donaldson, "How Will They Bring Us Back, 200 Years From Now?" **The Immortalist** 12(March 1981):5-10; K. Eric Drexler, **Engines of Creation: The Coming Era of Nanotechnology**, Anchor Press/Doubleday, New York, 1986, pp. 133-138; Brian Wowk, "Cell Repair Technology," **Cryonics** 9(July 1988), http://www.alcor.org/Library/html/cellrepairmachines.html; Mike Darwin, "Resuscitation: A Speculative Scenario for Recovery," **Cryonics** 9(July 1988):33-37, http://www.alcor.org/Library/html/resuscitation.htm; Thomas Donaldson, "24th Century Medicine," **Analog** 108(September 1988):64-80 and **Cryonics** 9(December 1988), http://www.alcor.org/Library/html/24thcenturymedicine.html; Ralph C. Merkle, "Molecular Repair of the Brain," **Cryonics** 10(October 1989):21-44; Gregory M. Fahy, "Molecular Repair Of The Brain: A Scientific Critique, with a Response from Dr. Merkle," **Cryonics** 12(February 1991):8-11 & **Cryonics** 12(May 1991), http://www.alcor.org/Library/html/MolecularRepair-Critique.html; "Appendix B. A 'Realistic' Scenario for Nanotechnological Repair of the Frozen Human Brain," in Brian Wowk, Michael Darwin, eds., **Cryonics: Reaching for Tommorow**, Alcor Life Extension Foundation, 1991, http://www.alcor.org/Library/html/nanotechrepair.html; Ralph C. Merkle, "The Technical Feasibility of Cryonics," **Medical Hypotheses** 39(1992):6-16, http://www.merkle.com/cryo/techFeas.html; Ralph C. Merkle, "The Molecular Repair of the Brain," **Cryonics** 15(January 1994):16-31 (Part I) & **Cryonics** 15(April 1994):20-32 (Part II), http://www.alcor.org/Library/html/MolecularRepairOfTheBrain.htm; Ralph C. Merkle, "Cryonics, Cryptography, and Maximum Likelihood Estimation," **First Extropy Institute Conference**, Sunnyvale CA, 1994, http://www.merkle.com/cryo/cryptoCryo.html; Ralph Merkle, "Algorithmic Feasibility of Molecular Repair of the Brain," **Cryonics** 16(First Quarter 1995):15-16; Michael V. Soloviev, "SCRAM Reanimation," **Cryonics** 17(First Quarter 1996):16-18, http://www.alcor.org/cryonics/cryonics1996-1.pdf; Mikhail V. Soloviev, "A Cell Repair Algorithm," **Cryonics** 19(First Quarter 1998):22-27, http://www.alcor.org/cryonics/cryonics1998-1.pdf; Robert A. Freitas Jr., "Section 10.5 Temperature Effects on Medical Nanorobots," in **Nanomedicine, Volume I: Basic Capabilities**, Landes Bioscience, Georgetown, TX, 1999, pp. 372-375; http://www.nanomedicine.com/NMI/10.5.htm; Ralph C. Merkle, Robert A. Freitas Jr., "A Cryopreservation Revival Scenario using MNT," **Cryonics** 29(Fourth Quarter 2008).



After the chromallocyte locates and docks with the cell nucleus, it extends a tool-tipped robotic arm into the nucleoplasm. The job of this nanorobot is to replace old damaged chromosomes with new ones in every cell.

A Cryopreservation Revival Scenario using MNT

By Ralph C. Merkle and Robert A. Freitas Jr.

We briefly outline one possible cryopreservation revival scenario using MNT (molecular nanotechnology). A full analysis will require much further work and detailed research. Our principal assumptions are that a reasonably mature MNT will exist, and that the patient has received a "good" cryopreservation by current standards, including the introduction of appropriate levels of cryoprotectants.

Pre-Repair Operations

The first question we face in designing a cryopreservation revival scenario is whether to warm the patient to provide a liquid environment before beginning, or to initiate repairs at low temperature (77 K for patients in LN2, or perhaps ~140 K for patients in the future who elect Intermediate Temperature Storage (ITS)).

The obvious disadvantage of warming before initiating repairs is that further deterioration will take place, which might result in the loss of personality-relevant information (e.g., warming might cause deterioration of synaptic or neurological structures). We know that current methods of cryopreservation cause fractures. While these fractures, like fractures in glass, are expected to produce minimal information loss, they would nevertheless create problems with structural integrity that, upon warming, could lead to further deterioration. Without some form of stabilization, warming fractures would be like slicing the tissue with incredibly sharp knives – on its face not something that we wish to do. Other forms of damage that had occurred either prior to cooling or during the cooling process might, upon warming, also cause continued deterioration of the tissue. As a consequence, initiating the repair process at low temperature is the more conservative approach.

The first step in low temperature repair is to clear out the circulatory system. This process would more closely resemble drilling a tunnel than anything else, and would require the use of molecular machines able to function at (for example) LN2 temperature (though the particular temperature could be adjusted as might be found useful).

This basic process will employ molecular machines that can operate at low temperature, and can sense and remove the kinds of materials found in the circulatory system. Fortunately, proposals for diamondoid molecular machines that operate at low temperature are common. Gears, bearings, ratchets, sliding interfaces and the rest work quite well regardless of temperature, and detailed analyses of molecular structures bear out this claim. Unlike biological systems that typically require liquid water in which to operate, diamondoid molecular machines can operate in vacuum with no need for lubricants and at temperatures as low as we might desire.

Logistics System Installation

Coordination, communication and power for these molecular machines can again be provided at low temperature. Designs for very compact molecular computers able to operate at arbitrarily low temperatures (specifically including rod logic, a type of molecular mechanical computation) are well known in the literature and could provide the computational power needed to coordinate repair activities. Several modes of communication are available, including molecular cables that should be able to transmit data at gigabit rates or higher (www.nanomedicine.com/NMI/7.2.5.htm). By coupling activity of onboard repair devices to off-board computational resources, the overall repair process could be guided by massive computational resources located outside of the patient, thus avoiding concerns about patient heating caused by waste heat from the computational resources required to plan and coordinate repair activities. Finally, power distribution can take place by whatever means is convenient (www.nanomedicine.com/NMI/6.4.htm), including distribution of electrical power via carbon nanotubes (which can have remarkably high conductivity).

During the repair process, various molecular inputs will be required and molecular outputs must be removed. A cryonics-specialized variant of an artificial vasculature or "vasculoid" (see www.jetpress.org/volume11/vasculoid.html) redesigned to operate at low temperatures could be installed to carry out this function. In this variant, the initial transport load would be orders of magnitude smaller than the load that a fully functional vasculoid would be required to handle in a normally metabolizing person even at basal rates. (The original vasculoid was scaled to handle peak metabolic rates.) Roughly speaking, a vasculoid is an artificial circulatory system that enables coordinated ciliary transport of containerized cargoes using a leak-tight coating of machinery on the inner vascular walls. The vasculoid appliance is readily modified to operate at low temperature, and can easily span relatively large cross-capillary breaks.

This initial stage brings medical nanodevices to within ~20 microns of any point in the brain via the circulatory system, and provides distributed power and control as well as massive computational resources located outside the tissue undergoing repair. Initial surveys of the tissue would provide damage estimates at specific sites, including a detailed mapping of fractures. A variety of imaging modalities (www.nanomedicine.com/NMI/4.8.htm) could be used to provide extensive information about the cellular structure throughout the immobilized tissue. At this stage, the external computer guiding repairs would come to possess detailed structural information of the entire system down to the cellular and subcellular level. If the cryo-

preservation had generally gone well, this fact would be apparent and relatively minimal analysis and repairs would be required. If the cryopreservation had produced more significant damage in some areas, this damage could be tabulated and assessed, and appropriate repair strategies could be planned. There is reason to believe that even very serious damage could be analyzed, the original healthy state determined, and appropriate repair strategies adopted (see, for example, "Cryonics, Cryptography, and Maximum Likelihood Estimation" at www.merkle.com/cryo/cryptoCryo.html).

Fracture Stabilization

Current cryopreservation methods create fractures, some of which can have gaps that are tens or even hundreds of microns across. Unstabilized, these fractures would cause further tissue deterioration upon warming. Stabilization of fractures can be done by the synthesis of artificial surfaces specifically designed to conform to the exposed faces of the fractures. For example, we could make a stable support sheet of ~1 nanometer thickness to which arrays of hydrophilic and hydrophobic molecular surface "decorations" are attached. By making the decorations match the exposed face of the fracture, this support sheet would stabilize the fracture face on warming and prevent further deterioration. The success of this approach depends upon the ability of MNT to synthesize an appropriate support sheet – which we expect to be well within the capabilities of the technology.

Following stabilization of fracture surfaces the system temperature can be slowly increased without risk that the fractures will contribute to further deterioration. The support sheet would remain in contact with the fracture face even as the fracture face expands or contracts during warming – the thin support sheet would readily conform to such changes in shape.

Tissue Chemistry Restoration

As the temperature increases and some degree of fluidity is reintroduced into the tissue, the repair process can turn to other issues. In particular, some proteins have likely been denatured during the cryopreservation process. As most proteins should spontaneously recover, the technical challenge will be to identify those that are slow to recover and then either hasten their recovery (possibly by the use of artificially designed chaperones) or support their missing function by other means during recovery. (The recovery of many tissue types after cooling to low temperature supports this approach – if any significant fraction of proteins failed to recover, one would not expect any tissues to spontaneously survive such treatment.) In those cases where critical functionality does not spontaneously recover with sufficient rapidity, it would be possible to introduce new properly folded proteins at an appropriate temperature to take over the critical functions that have been compromised, and then let the tissue recover by itself later on, once it has resumed normal functioning. Re-denaturation of proteins can largely be avoided by delaying repairs to higher temperatures in a series of stages depending on which repairs are needed at various temperatures.

The cryopreservation process and the changes prior to cryopreservation have likely caused imbalances in the concentrations of specific chemicals. Concentrations of sodium, potassium, other ions, ATP, glucose, oxygen, and many other metabolites and chemicals are likely not at desirable values. Concentrations of cryoprotectants might or might not be at desired levels for the particular temperature, so it might be useful to remove cryoprotectants employed during the cryopreservation and replace them with newer cryoprotectants that have more desirable properties. As the tissue becomes more fluid, concentrations of any specific chemical can be measured and adjusted. Direct access to cells surrounding the capillary lumen is available, and the use of tubular probes (which could be introduced from the luminal vasculoid face once the liquid environment becomes sufficiently viscous to allow such probes to penetrate) would provide direct access to the intracellular contents of cells 10 or 20 microns from any capillary. Concentrations of reactive molecules such as oxygen and other reactive metabolites would be kept low until later in the recovery process, with metabolism also kept on hold during this time.

The support system and external computer would have essentially total control over the concentration of all chemical compounds in all cellular and even subcellular compartments in the recovering patient. The control system would adjust these concentrations as needed to minimize damage, both during the re-warming process and also later while metabolic activities were being re-established.

Fracture Sealing and Comprehensive Cell Repair

At some higher temperature, with sufficient fluidity for tissues to flow and reduce strain, the fracture faces can be brought together and the support sheets removed and exported from the body. One simple conceptual mechanism for bringing the fracture faces together involves using biologically inert "strings" attached to specific matching sites on two support sheets that are stabilizing the two opposing faces of a particular fracture. Pulling the strings tight draws the opposing fracture faces together. Even fracture gaps as large as 0.5 millimeters can be accommodated, since all the individual support sheets in a large block of tissue can be simultaneously manipulated as an incremental three-dimensional global strain release network to slowly heal the breaks.

Once the system is liquid it becomes possible to introduce other medical nanodevices to deal with specific forms of damage, including pre-existing damage – like the presence of lipofuscin or other undesired intracellular or extracellular junk, nuclear mutations or epimutations (http://jetpress.org/v16/freitas.pdf), damaged mitochondria (which could simply be removed and replaced with new, functionally correct mitochondria), and a wide range of other conditions.

Patient Wake-up

After the patient has been repaired, stabilized and warmed to conditions of moderate hypothermia, metabolic activities and concentration gradients appropriate to a healthy functional state can be re-established. The vasculoid increases its transport activities to levels appropriate for a healthy human under normal conditions. The vasculoid can then be removed (in accordance with the sequence described in the vasculoid paper) and the patient is now fully restored but unconscious. Finally, the person is gently ramped through mild hypothermia up to normal body temperature with initiation of consciousness and full awareness of surroundings. The patient is now awake and healthy. ■

Interview with Robert Freitas & Ralph Merkle

1. How and when did you get interested in nanotechnology and cryonics?

Freitas: For me, cryonics and life extension came first. In 1968 at the age of 15, I wrote the first 55 pages of an unfinished science fiction novel about a teenager who volunteers to be placed in a time capsule and frozen using the new science of "cryobionics." The computer controlled facility was programmed to wake the traveler every century or so, whereupon he would emerge from a hidden high-tech mountain lair and explore first-hand the progress mankind had achieved during his frozen slumber. "Why do it?" the boy was asked. "Curiosity," he replied. "I want to see how man's technology will grow, and how man himself will change, through the years." Today, 41 years later, I'm still motivated by this same curiosity about the future, but I'm driven even more strongly by the desire to actually create that future – and to find a way to directly experience it, in person.

I believe the first time I ever thought about atomic-scale engineered objects was in 1977 while working on my first treatise-length book project, titled *Xenology* (www.xenology.info). In Section 16.4.1 of that book, I wrote about using molecular electronic components to create a computer system having 10 billion "microneurons" in the space of few microns, "small enough to hide inside a bacterium". During my NASA work on self-replicating machines in the early 1980s, I'd wondered how small machine replicators might be made, studied emerging micromachine technologies, and written about bloodstream-traveling surgical robots in 1985 in a book edited by Minsky. But it wasn't until 1994 that reading Drexler's *Nanosystems* confirmed what I already suspected based on my own knowledge: namely, that the technical case for molecular nanotechnology (MNT) was very solid. (I didn't read *Engines of Creation* until later.)

It was clear that nanomedicine offered a chance for radical "healthspan" (healthy lifespan) extension. This was especially exciting because it also appeared that this objective might be achievable within the several decades of life actuarially remaining to me and others of my generation – but only if we moved quickly. So, was anyone pushing this forward? I spent half a year reading every nanotechnology-related book, paper, and article I could lay my hands on. Back in 1994, the technical discussion was still mired in debates over whether or not nanotechnology was possible at all, and the popular discussion mostly dealt with general objectives or with hoped-for capabilities, without a lot of technical content and with very few specifics. I contacted the Foresight Institute and was told that nobody had yet written any systematic treatment of the medical area, nor was anyone planning to do so in the near future. So I took up the multi-year challenge of researching and writing the *Nanomedicine* book series (www.nanomedicine.com) the first book-length technical discussion of medical nanorobotics. Two volumes were published in 1999 and 2003 with two more in progress, and scaling studies for seven different medical nanorobot designs (including the first cell repair device) have been completed since then.

By 2001, it became apparent that there was no serious molecular manufacturing development going on, either. Frustrated, while at Zyvex I initiated (with Ralph Merkle) a systematic effort to achieve this development that has become known as the Nanofactory Collaboration. We began publishing paper after paper in mainstream peer-reviewed technical journals, doing the hard work of sweating the details of atomically precise manufacturing to fill in the first steps leading toward nanofactory design. Along the way we've published a book on replicative manufacturing systems (www.MolecularAssembler.com/KSRM.htm) and performed a lot of useful research with many interesting collaborators around the world.

Merkle: I had a very different experience. I never thought about either life extension or cryonics until I was in my 30's and had completed my Ph.D., gotten married, bought a house, and settled into a Silicon Valley start-up company. As was my habit, I began thinking about my next steps and long-term plans. At first, I saw smooth sailing for several decades.

Then I would die.

While traditional, it was not clear that this was either necessary or desirable. I began to review the relevant literature. Cryonics was simply one of the items on my list of possibilities, and not very high on my list at that. My initial intuition was that the human body was a very complex machine which had not evolved to cope with freezing. This intuition persisted through my review of cryobiology, but I rapidly concluded that cryonics – unlike any other approach – could benefit from future technology developed any time in the course of the next few centuries. This led me to review the fundamental limits of what would be possible and whether the kind of injuries that occur during cryopreservation would eventually be reversible.

This was a rather complex undertaking, but after reviewing and considering the available literature it was pretty obvious that cryonics, assuming any reasonable care in cryopreservation, would almost certainly work. (I wish to thank the Xerox PARC library staff who tracked down the articles from any reference I gave them. Some of the references were, even by PARC standards, pretty unusual!) Once I had completed the analysis to my personal satisfaction, I decided that, with a little more work, I could make the results available to others. This led to the publication of "The Technical Feasibility of Cryonics" in *Medical Hypotheses* in 1992 and a more extensive version titled "The Molecular Repair of the Brain" in *Cryonics Magazine* in 1994.

At this point, I found myself in the almost unique position of having carefully analyzed the feasibility of molecular nanotechnology. Aside from Richard Feynman, Eric Drexler and perhaps a few others, almost no one had realized that this new technology was even possible, let alone that it would fundamentally change the world. Given the raw magnitude of the impact, and my fortuitous position in a cutting edge research institute charged with developing fundamentally new technologies, I decided to pursue molecular nanotechnology professionally. I expected that others would realize, within a few years, the magnitude of the opportunity and jump in. *Engines of Creation* by Drexler was very readable and entirely persuasive to someone with the right technical background, and the famous Nobel Prize winning physicist Feynman had placed his stamp of approval

Robert A. Freitas, Jr.

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Ralph C. Merkle

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on the whole endeavor back in 1959 in "There's Plenty of Room at the Bottom."

Much to my amazement, molecular nanotechnology was deemed controversial and its basic feasibility was attacked by many "respectable" scientists. That their arguments were technical gibberish coated with a thin veneer of impressive-sounding words was both a comfort (they obviously had found no holes in the argument) and a problem (they succeeded in misdirecting both people and research funds towards incremental and evolutionary research).

I had seen this pattern before in public key cryptography. My first work in this area was roundly rejected as "...not in keeping with current cryptographic thinking." It took a few years before the research community realized that public key cryptography was, indeed, a major advance. This pattern is common in science (and indeed, in all areas of human endeavor): new ideas are initially rejected and later accepted only slowly (see www.foresight.org/News/negativeComments.html).

I thought that, with a little patience and some clear explanations, the same pattern would be followed in molecular nanotechnology. I began giving talks and writing papers that illustrated the basic concepts, provided worked examples of the kind of research that was needed, and clarified points that seemed to cause confusion. While there has been a slow acceptance of the basic ideas, it has been much slower than I initially anticipated – perhaps because molecular nanotechnology is based on the synthesis of ideas from several fields and the typical research scientist is only educated in one or two. To grasp the whole requires an understanding of ideas typically found scattered in different disciplines.

Unfortunately, rapid technical progress requires research funding, which is largely committee based. Even though there are now quite a few strong supporters, a randomly selected committee of research scientists will typically have at least one or two members who roundly reject any attempt to pursue molecular nanotechnology, thus blocking any funding.

The alternative is to find individual decision makers who can both understand the value of molecular nanotechnology and have the resources to back up their intuition with funding. Such people are often called "patrons," "angel investors," or just "wealthy," but whatever you call them the result is that research can be funded without having to first persuade 90% of the research community that it is a good idea.

2. Developing molecular nanotechnology looks like a daunting task. How are you going to approach this?

Our general approach is summarized at the Nanofactory Collaboration website (www.MolecularAssembler.com/Nanofactory). First, we target the strongest known materials – fullerenes, diamond, and related ultrahard ceramics, collectively called diamondoid. Second, we develop the engineering discipline known as positionally controlled mechanosynthesis – the fabrication of atomically precise structures using atomically precise tools driven by mechanical forces to drive the chemistry. Third, we use this new fabrication technology to build nanoscale molecular machinery, such as bearings, gears, motors, pumps and robotic arms. Fourth, we develop more complex nanoscale machinery that can itself build machinery of the same general

kind. Fifth, we scale up using massively parallel assembly lines.

The result will be a working nanofactory. The nanofactory is a proposed compact molecular manufacturing system, possibly small enough to sit on a desktop, that could build a diverse selection of large-scale molecularly precise diamondoid products. The nanofactory is potentially a high quality, extremely low cost, and very flexible manufacturing system.

3. What are the benefits of molecular manufacturing?

Molecular manufacturing will continue three great multi-decade and even multi-century trends in manufacturing: greater precision, greater flexibility, and lower manufacturing cost. Molecular manufacturing will give us the ultimate in precision (essentially every atom in the right place), the ultimate in flexibility (the ability to arrange atoms in almost any specified pattern consistent with physical law), and the ultimate in low cost (manufacturing costs not much greater than the cost of the required raw materials and energy).

Almost all manufactured products will be remarkably light, strong, smart and inexpensive. The manufacturing process itself will be pollution free. MNT will give us supercomputers that fit inside a living cell, solar power perhaps 100 times cheaper than today's electricity (eliminating the need for polluting coal, oil and nuclear energy plants), reliable and effective medical nanodevices, and more.

More succinctly: molecular nanotechnology will make us all healthy and rich (at least in a material sense).

4. What needs to be done to speed progress?

Theory, experiment, planning, resources, and action.

With dozens of collaborators at 11 institutions in 4 countries, over the last 10 years we've laid the foundations for molecular manufacturing development with a series of theoretical papers and planning documents analyzing all the basics.

We're collaborating with an experimental team led by Philip Moriarty, a leading U.K. scanning probe microscopist at the University of Nottingham, who is attempting to fabricate and test several of the mechanosynthetic tooltips and processes we've analyzed theoretically.

Now we need to mobilize the (larger) resources needed to develop atomically precise fabrication, molecular manufacturing, and nanofactories. Once we get the resources, we're ready to go.

5. If someone wants to accelerate the development of MNT, what should they do?

Contact us. We have a plan.

There are times when a small group, funded by a visionary patron, can change the world for the better. DARPA and the internet. Nobel and his Prize. Kennedy and the moon landing. Queen Isabella and Columbus.

Who will be remembered for molecular manufacturing?

Perhaps you? Or someone you know? ■