MIT’s new Center for Bits and Atoms (CBA) is an unprecedented initiative to look past the end of the Digital Revolution in order to bring together the best features of the bits of new digital worlds with the atoms of our physical world. It is here at this interface that many of the most compelling opportunities lay for the future intellectual, social, and economic impact of information technologies.

The last few decades have seen a growing division between bits and atoms, as both academia and industry were organized around boundaries between hardware and software, between channels and the content they carry, between Computer Science and Physical Science, and ultimately between the study of the minds and bodies of machines. But the continued scaling of VLSI circuitry is itself erasing these distinctions as transistors shrink down to the size of individual atoms, memory cells approach holding single electrons, and, perhaps most urgently, the cost of a chip fab plant grows towards the scale of national GDPs. These limits have long been recognized as looming technological constraints; what was not widely appreciated was the extent to which they also represent great opportunities.

The physical systems that are used today for computing and communications offer means for manipulating information that go far beyond those assumed by a digital programming model that has remained unchanged for decades (if not centuries). Beyond just surpassing the limits of conventional device scaling, these new capabilities promise to help address the greatest information technology scaling limit of all: relevance. The most significant technological needs of the greatest number of people are not for faster computers with more memory, they are for mechanisms that can bring the impact of information technology out of the digital world of computers and into the physical world of people. This is the mission of the CBA.

The CBA vision is to assemble an integrated suite of experimental resources that will make it possible to simultaneously shape the information in a system and its physical properties, from atomic nuclei to global networks. These tools will be surrounded by an intellectual community that cuts across traditional divisions of length scales and levels of description in order to directly address questions at the bit-atom boundary. With backgrounds in biology, chemistry, physics, and mathematics, as well as computer science, electrical, and mechanical engineering, the organizing principle for their collective inquiry is defined by the relationship between the content of information and its physical representation rather than by the boundaries of academic disciplines.
These people and their machines will be housed in a new building designed by Pritzker Prize-winning architect Fumihiko Maki, with unique open laboratories that look and feel more like an architect's atelier but that will house nanofab clean rooms, biology and chemistry labs, machine and instrumentation shops, rapid-prototyping tools, and high-bay assembly workspaces. The technical services required for these resources are being provided through advanced floor and ceiling systems rather than conventional laboratory cores in order to preserve the openness of the workspaces. And accommodating the unusual program adjacencies between the labs and partner groups ranging from young children to performing artists has entailed turning the whole building into a testbed for Internet-enabling the physical plant, through the development of ultra-lightweight embedded IP nodes along with distributed data structures and algorithms, so that the physical plant itself can be responsive to the changing needs of all of the building's occupants. Site preparation for this building has been completed, with construction starting later this year and occupancy in 2005. In advance, CBA will be housed in renovated labs in the Media Lab's present I.M. Pei building.

**Grand Challenges**

The prospective work of the CBA can best be understood through some of the core beliefs inspiring present and planned research:

**Digital logic was a bad idea**

A seven quantum-bit molecule used to implement polynomial-time factoring [1,2], and an analog circuit acquiring a digital code [4]

Our reliance on digital logic dates from the profound insights from Alan Turing (~1936), John von Neumann (~1945), Claude Shannon (~1948), and others, that it is possible to program a general-purpose digital computer to solve, without errors, any problem up to the limit of its size and your patience, and before that from Charles Babbage (~1834), George Boole (~1854), and others, that machines can be made to manipulate abstract symbols. These are arguably the most profound and consequential abstractions in the history of any technology. But they are indeed abstractions, which succeed by the extent to which they hide the details of the physical systems used to implement them. This ignorance is increasingly hard to sustain as the scaling of information technology is reaching fundamental physical limits; further progress can come only by taking advantage of resources of physical systems that are missed by a digital abstraction, and hence will rely on reconnecting bits with the atoms that represent them. Classically, CBA researchers have shown that the continuous degrees of freedom of analog circuits can be used to realize optimal digital functions with savings of orders of magnitude in speed, power, or parts [4,5]. And we've used the exponentially-greater number of degrees of freedom in quantum-mechanical systems to factor [2] and search [3] in fewer steps than are required classically. The latter experiments computed by
programming the dynamics of nuclear spins in molecules rather than by attempting to fabricate nanostructures that reach atomic scales; the recognition that natural systems can compute not only points to the prospect of synthesizing rather than expensively manufacturing computing devices, it hints at the power of a computational language in explaining the behavior of physical systems.

**Bugs will have programs**

![Electronic detection of DNA](image)


Biological metaphors are used increasingly frequently to describe computing systems, and *vice versa*; we're finding that this connection is in fact a literal and bidirectional one all the way down to molecular scales. On the input side, we've shown that silicon surfaces can be functionalized with DNA to create digital logic that switches based on the presence of particular proteins, with single-base selectivity [6]. Such direct electronic detection has enormous implications for drug discovery, elucidating cellular signalling pathways, and understanding the proteome. It becomes more significant still when coupled with another dramatic result: electronic control of protein structure [7]. By attaching gold nanocluster antennas to proteins it's possible to change their conformation under radiofrequency irradiation and thereby switch their function. Biotechnology is based on manipulating gene expression, but these genes get fixed in cells that express them. The invention of "RF biology" suggests that multiple genes can be switched on and off in a single cell in real time. And, when coupled with electronic protein detection, this in turn means that it will be possible to close a feedback loop to operate real-time control systems in cells. The significance of having such biological equivalents to analog-to-digital and digital-to-analog converters follows from the relatively simple genetic sequences that code for enormously complex organisms (the smallest complete genome contains just a few hundred genes) by encoding functional relationships that produce final structures rather than by specifying the details of those structures. This is in fact a kind of natural programming, and by being able to not only read but write this language in real time it may be possible to explicitly program cells to manufacture desired nanostructures.

**Engineers will not design complex systems**
If it becomes literally possible to grow enormous numbers of computers at negligible cost, one thing is certain: current engineering practice for designing systems will fail at this tremendous scale. As the number of interacting elements in a system passes from millions to billions to trillions of components, whether it’s transistors in a circuit, connections in a power grid, or computers in a network, both the systems and their supporting design tools begin to fail in unexpected and often unexplained ways. One of the greatest challenges for CBA will be to design not systems but the principles by which enormously complex systems come to function without actually understanding how they do it. This will entail bringing the rigor with which parameters such as bandwidth, power, and noise are now optimized to attributes such as hierarchy, emergence, and adaptation. An early example is "paintable" computing [8], which replaces large chips wired onto circuit boards with many small chips randomly distributed in a bulk medium so that information processing can be poured out by the pound or painted onto a wall. To program such a fungible computer, mobile code propagates through the medium to discover the geometry and available functionality and configure it for a particular task. This new kind of programming model is of immediate interest as an alternative to the increasingly-prohibitive economics of fabricating ever-larger devices with perfect yield, but even more importantly it provides a working example of how to engineer emergent behavior in enormous systems of imperfect components.

The future of Personal Computation is Personal Fabrication

The Personal Computer has been the embodiment of the Digital Revolution. Mainframes were expensive machines, used for industrial operations with limited markets by skilled operators working in specialized spaces. When the packaging of computation made it accessible to ordinary people, the inventiveness and common sense of ordinary people could then tailor it to personally-meaningful applications, and the result was the explosive spread of information technology. Compare this history to the present state of machine tools, which are expensive machines, used for industrial operations with limited markets by skilled operators working in specialized spaces. If success can be declared in the Digital Revolution and the coming story is going to be how those newly-freed bits connect to the rest of the world, then with the benefit of hindsight the embodiment of this new revolution will be Personal Fabricators. We’ve shown that it's possible to use table-top processes to print logic, sensors, actuators, and displays along with three-dimensional structures [9,10]. By integrating these capabilities into a single printer that in addition to colored inks contains n- and p-type semiconducting, insulating, and structural inks, the result promises to be one...
The most advanced information technologies are needed in the least developed places

When computing moves out of traditional computers and into the world, it becomes relevant to the rest of the world for whom today’s information technologies are now irrelevant. The greatest demand for, and consequences of, the proceeding projects lie in places that are beyond the reach of incremental engineering improvements on existing solutions. Some of the most intractable problems in global development require the highest rather than the lowest technologies; perhaps the grandest challenge of all for CBA will be to develop the connections between fundamental research and its urgent applications, such as:

- Bringing Internet access to all of the children on the planet will require bringing the economics of printing to the deployment of the Internet.
- For commerce to be able to reach rural artisans electronically, they will need to be able to personalize fabrication as well as computation.
- Where biometrics are used in developed countries to protect institutions from bad people, they need to be usable elsewhere to protect people from bad institutions.
- The global demand for healthcare and environmental conservation will require integrating analytical instrumentation with embedded intelligence to provide the capabilities of advanced laboratories for the people who most need them, in a form that can go where the people are rather than where the labs are.

CBA is developing enabling technologies in these areas, which are guided and deployed through close collaboration with partners including the Media Lab Asia [12] and the Computer Clubhouses [13]. The heart of this effort is the establishment of field "fab labs," providing rapid-prototyping and instrumentation tools to enable underserved communities to design and produce as well as use appropriate information technologies.
CBA is growing out of MIT's Media Lab, which was launched by Nicholas Negroponte in 1980 with a vision of freeing digital information from the constraints of traditional physical media. The Media Lab was co-founded by Jerome Wiesner, who was MIT's President and President Kennedy's Science Advisor. For Prof. Wiesner, the Media Lab was a final grand experiment in organizing inquiry, seeking to break down the divisions among disciplines, between short- and long-term research, between academia and industry, and, most importantly, between fundamental research and the content of its applications. The Media Lab in turn emerged from MIT's Architecture Machine Group, bringing the atelier character of an architect's studio to the practice of technological research. The success of this meta-experiment is perhaps the most significant of all of the Media Lab's technical contributions.

The Media Lab is now becoming an international network of Media Labs, all sharing a culture of research happening in shared workspaces that draw on a range of disciplines to tackle emerging grand-challenge problems, but differing in their individual foci. Along with the Media Lab Europe (based in Dublin) that is broadly exploring information technology's cultural context, and the Media Lab Asia (based in India) that is looking at its consequences for global development, CBA can be thought of as extending the sensibility of the Media Lab at MIT to the domain of physical science.

This growth in research scope will be mirrored by an expansion of the associated academic context. Graduate degrees and faculty appointments in the Media Lab come from the Media Arts and Sciences (MAS) program; a new path to specialization in Information and the Natural Sciences (INS) will be developed under the auspices of an expanded MAS (led by Bill Mitchell) that will provide a solid grounding in the intellectual and physical tools across the Media Labs, while accommodating the differing modes of inquiry and specialized study needed for advanced research in CBA's areas. This will draw on classes developed under MAS, including MAS.863 (How to Make (Almost) Anything), MAS.864 (The Nature of Mathematical Modeling), MAS.862 (The Physics of Information Technology), MAS.961 (Quantum Information Science), MAS.962 (Silicon Biology), and MAS.967 (Technology and Entrepreneurial Strategy), as well as classes taught with partners around campus, including 6.151 (Microfabrication Project Laboratory) and 8.14 (Junior Physics Laboratory). Students whose intellectual homes do fit into existing departments will be able to get degrees through them for thesis research in CBA, and undergraduates will be essential CBA participants via MIT's UROP program. Through this hands-on laboratory involvement, undergrads
become part of flexible intellectual workgroups that can provide "just-in-time" training rather than the more traditional academic norm of "just-in-case" education.

The Media Lab has primarily been funded, by design, by corporate sponsors because of the value of their intellectual as well as financial contributions. While CBA will continue this tradition of close industrial partnership, both government and philanthropic funding will play a greater role in supporting its significant capital investments and long-term research questions (CBA was inaugurated by a $13.75M National Science Foundation award [14], supporting its technical infrastructure along with the students and outreach activities to take advantage of it).

Many of CBA's initial projects grow out of work that was done in the Things That Think industrial consortium, founded in 1995 to broadly explore computing outside of traditional computers [15]. CBA will continue to work closely with TTT (which will remain under Media Lab management), and will bring in new sponsors meeting around its specialized research areas. CBA and the Media Lab will develop separate intellectual property pools, to accommodate the differences in how IP is managed in their respective areas, but these will be easily shared through joint sponsorship. From two years following the administrative launch of CBA (until July 1, 2004), Media Lab and CBA sponsors will receive access to both IP pools, after which they will become available separately under contract renewals. During this transition period CBA will not accept support from current Media Lab sponsors that reduces their Media Lab commitment. Beyond access to its intellectual property, current Media Lab sponsors can join CBA to work with its programs and resources, and new sponsors can join CBA at levels with or without royalty-free access to CBA IP, and with or without Media Lab joint sponsorship. CBA and the Media Lab will share and jointly support "back office" functions (including finance, contracts, facilities, computing, and human relations), but will separately manage "front office" functions such as their sponsor relations and external communications.

The core faculty members moving from the Media Lab to launch CBA are Joseph Jacobson, Scott Manalis, Isaac Chuang, and Neil Gershenfeld (who is CBA's first Director), aided by Marvin Minsky (and many others). CBA members will continue to pursue their close collaboration with people and projects across the Media Labs; MAS faculty members receiving support from CBA include Cynthia Braezeal, Joe Paradiso, Sandy Pentland, and Mitch Resnick. And a growing network of researchers throughout MIT are being supported by CBA for work at the bit-atom boundary that cuts across departmental boundaries, including Kim Hamad-Schifferli (Mechanical Engineering), Tom Knight (Electrical Engineering and Computer Science), Seth Lloyd (Mechanical Engineering), Rahul Sarpeshkar (Electrical Engineering and Computer Science), Larry Sass (Architecture), Sebastian Seung (Brain and Cognitive Science, Physics), Alex Slocum (Mechanics Engineering), Tim Swager (Chemistry), Karen Sollins (Electrical Engineering and Computer Science), and Shuguang Zhang (Bioengineering). CBA's first Program Manager is Sherry Lassiter, who, with a background in directing and producing scientific journalism (including work for Nova and Scientific American Frontiers), will be helping "produce" CBA's scientific work. This research is supported by technical staff including Bill Butera (IC design/fab), Bakhtiar Mikhak (outreach), John DiFrancesco (macrofabrication), and Ashley Salomon (microfabrication).

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