NSF CCR-0122419
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Activities and Findings

1. **Describe the major research and education activities of the project.**

   The Center for Bits and Atoms is an interdisciplinary initiative exploring the interface between physical science and computer science. CBA comprises roughly 15 research groups from across MIT's campus, including physicists, biologists, chemists, mathematicians, computer scientists, electrical and mechanical engineers, and architects, all working at the boundary between bits and atoms.

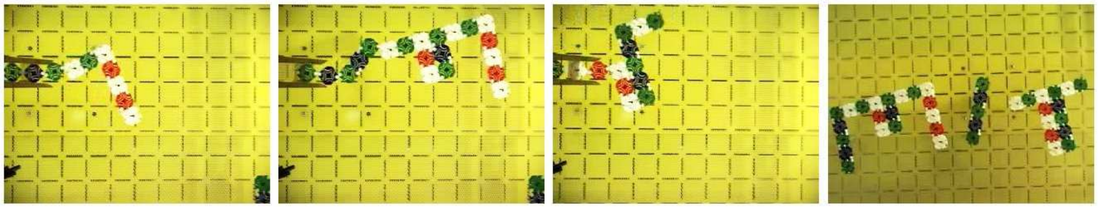
   CBA researchers have programmed the dynamics of systems ranging from nuclear spins to trapped ions to genetic regulatory networks to microfluidic flows to mechanical structures to analog logic circuits to conformal computing substrates. These pioneering experiments are approaching a limit in which the number of information-bearing degrees of freedom becomes comparable to the number of physical ones. Beyond this point it's no longer possible to distinguish between computer science and physical science, because they're describing the same attributes. CBA's research is revisiting the foundations of both, by exposing rather than hiding the boundary between hardware and software. Among the consequences of investigating this fundamental connection, CBA's work has:

   - Developed device mechanisms and programming models to effectively turn computation into a raw material that can scale to a limit of thermodynamic complexity
   - Applied the language of computation to model and measure computationally-universal physical systems, as a complement to differential equations as an earlier kind of information technology
   - Brought the programmability of the digital world to the physical world through bits that can transport materials as well as information, digitizing fabrication with programs that can not just describe things but *be* things

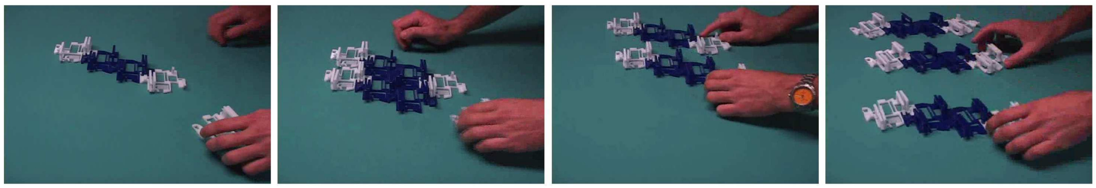
   CBA's research program is enabled by its investment in shared research infrastructure for input and output from nanometers to meters, and is supported by specialized training through a number of associated project-based classes. The work reaches beyond campus through topical meetings that have assembled emerging research communities in these areas, technology transfer via a number of industrial collaborations, and outreach through field "fab labs" that are bringing prototype tools for personal fabrication around the world.

2. **Describe the major findings resulting from these activities.**

   A core research theme across CBA's activities is the digitization of fabrication, investigating the programmed rather than self-assembly of materials that can locally encode global structures. Fundamental principles of digital fabrication have been demonstrated [Griffith *et al*., 2005], including arbitrary shapes folded from a one-dimensional magnetic code:



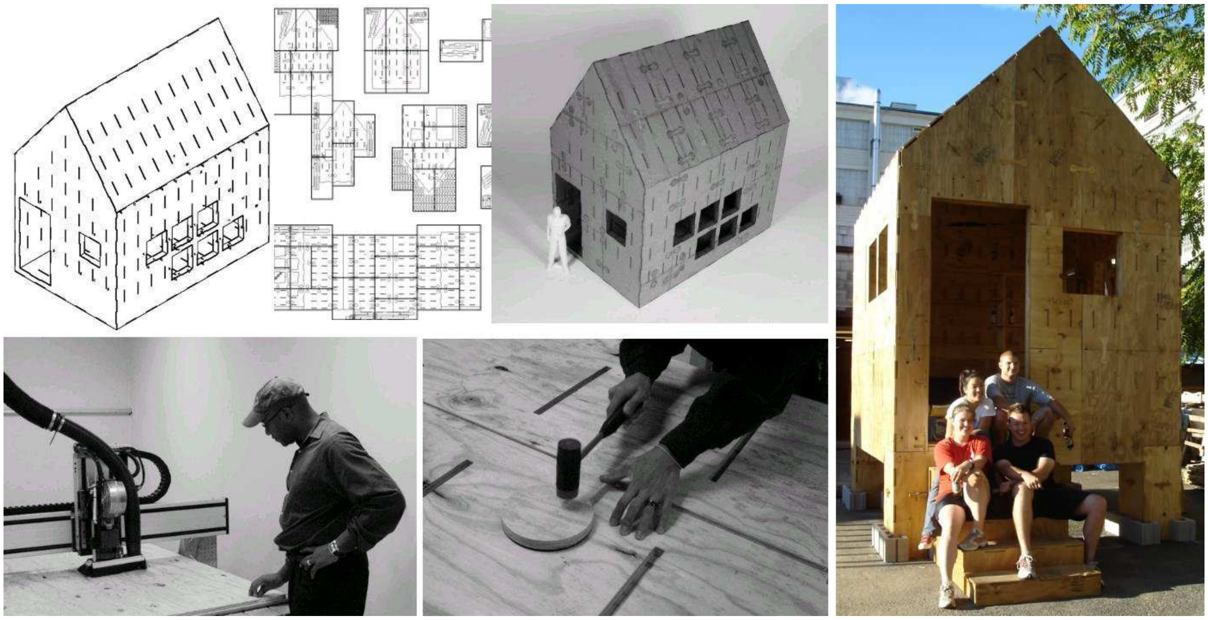
templated replication of a string of mechanical finite-state machines:



and error-corrected growth of a perfect crystal formed from electromechanical tiles:

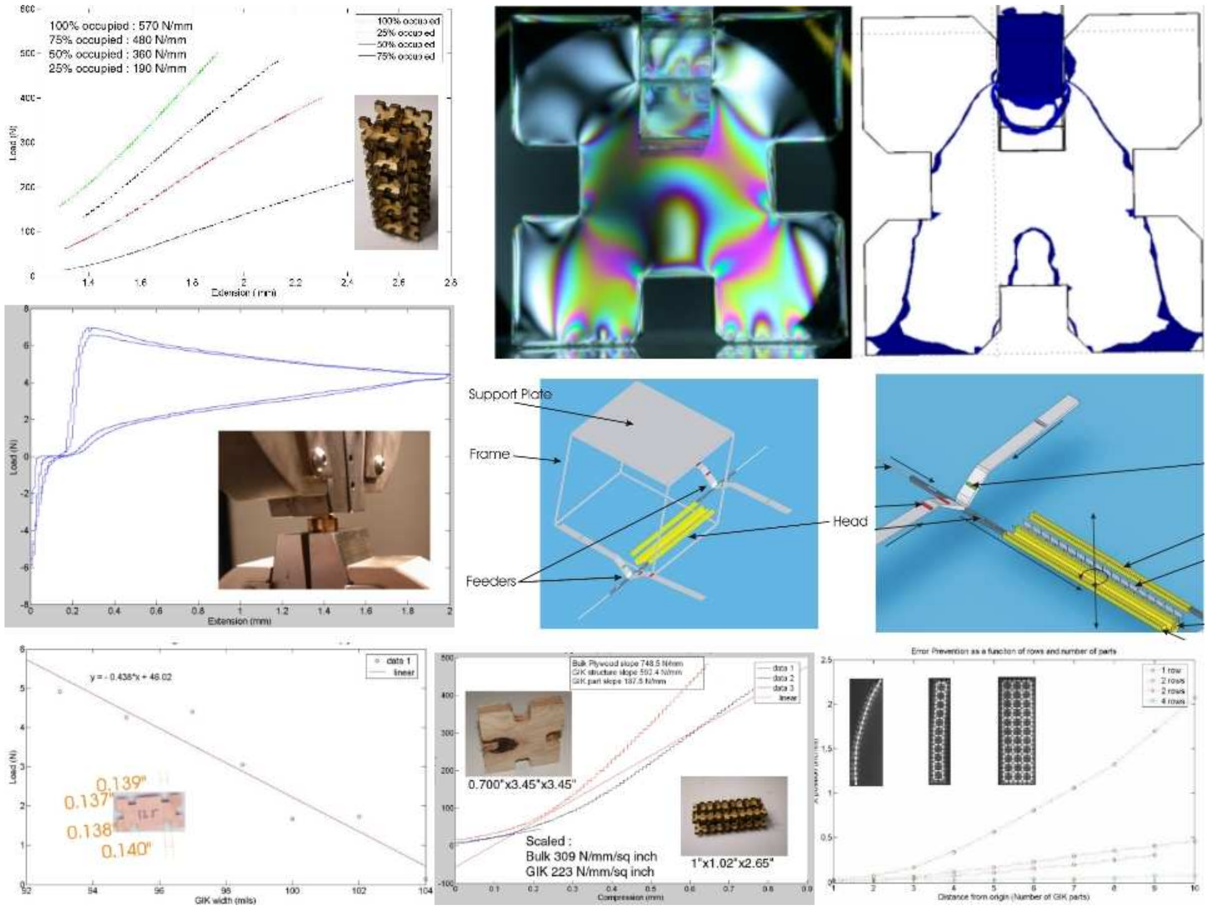
Analogous to the earlier results that formed the basis for the digitization of communications and computation, theoretical work in CBA is addressing questions including error-correction thresholds in fabrication and geometrical universality. In [Griffith *et al*., 2005] it was shown that the problem of finding a non-intersecting path to fold an arbitrary structure (equivalent to the Hamiltonian Path problem) can be reduced to the much simpler task of finding a spanning tree by increasing the spatial resolution by a factor of four in 2D or six in 3D, with a constructive solution using four types of vertex-connected squares in 2D or two types of edge-connected right-angle tetrahedrons in 3D.

Related CBA activities across a wide range of length scales are investigating the foundations of fabrication in locally encoding global structures. Macroscopically, a "shape grammar" for wood frame construction was developed to represent the design of a building in coded joints:

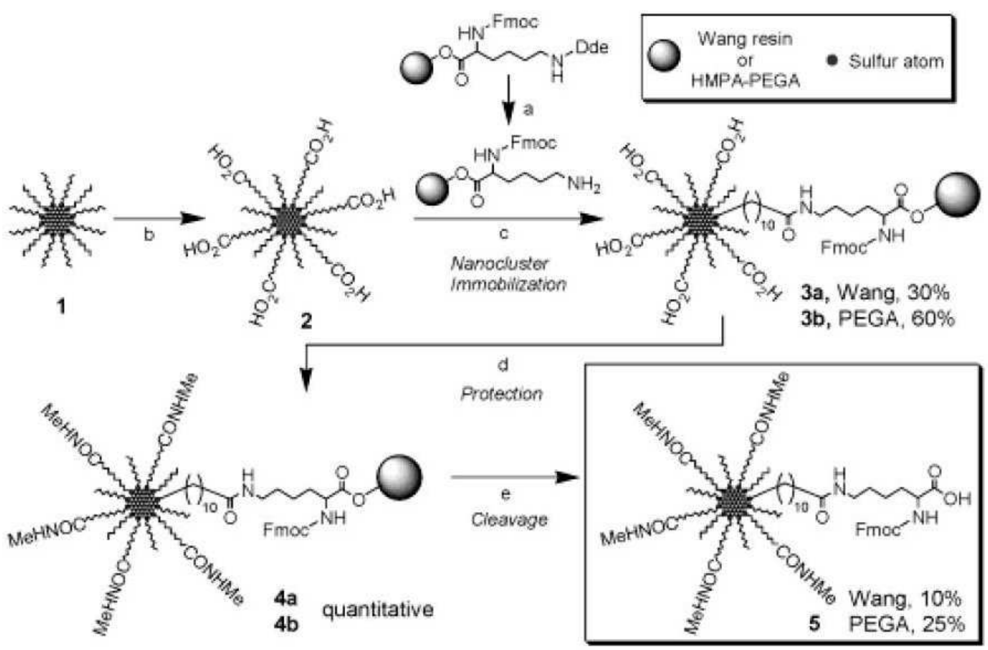


which can be assembled from press-fit panels produced with two-dimensional rapid-prototyping tools. This approach promises to reduce the cost of construction in time, labor, and materials, and even more importantly to enable rapid customization of low-cost construction that is responsive to local needs [Sass, 2005; Sass and Botha, 2006]. Current work is investigating the automated assembly of large-scale digital structures [Cheung and Gershenfeld, 2008]:

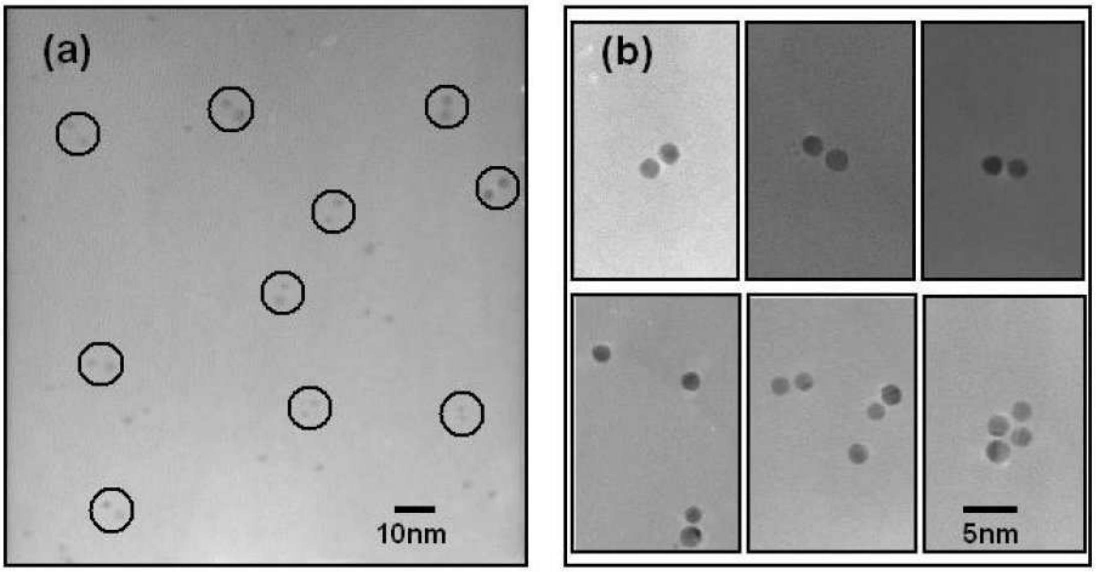
On mesoscopic scales, CBA researchers are developing the materials science of functional digital materials, with properties that can be tuned through their reversible assembly [Popescu *et al.*, 2006]:



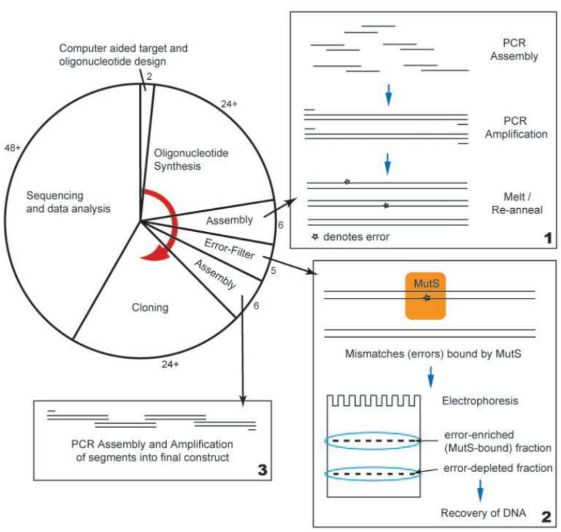
Microscopically, peptides were used to assemble nanoparticles. Monofunctionalized gold nanoparticles were synthesized with L-lysine (Lys) linkers by a solid-phase reaction using 4-hydroxymethylphenoxyacetyl (HMPA) -- polyethylene glycolacrylamide copolymer (PEGA) resin [Sung *et al*., 2004]:

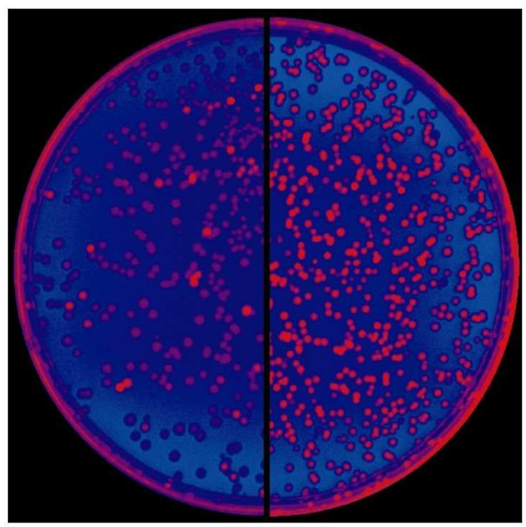


The monofunctionalization was confirmed by HRTEM observation of dimerization of the nanoparticles:

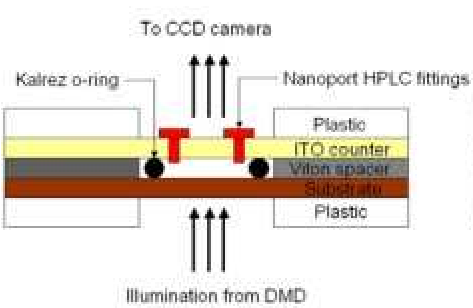


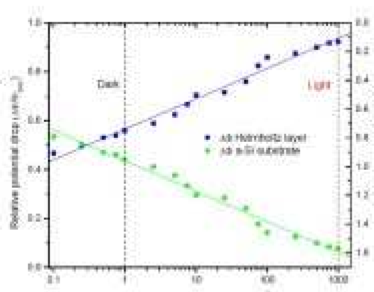
On molecular scales, the detection and removal of errors in the assembly of oligonucleotides was demonstrated, with a goal of reliable de novo synthesis of gene-length DNA. The mismatch-binding protein MutS (from Thermus aquaticus) was used to eliminate failure products from synthetic genes, shown here on the right applied to the expression of Green Fluorescent Protein (GFP) (greater than 95% of colonies fluorescent) [Carr *et al.*, 2004]:

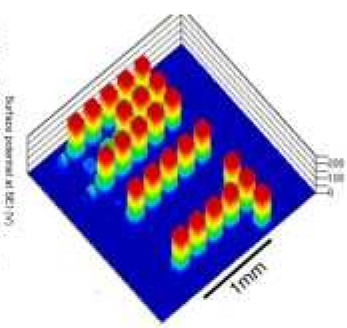




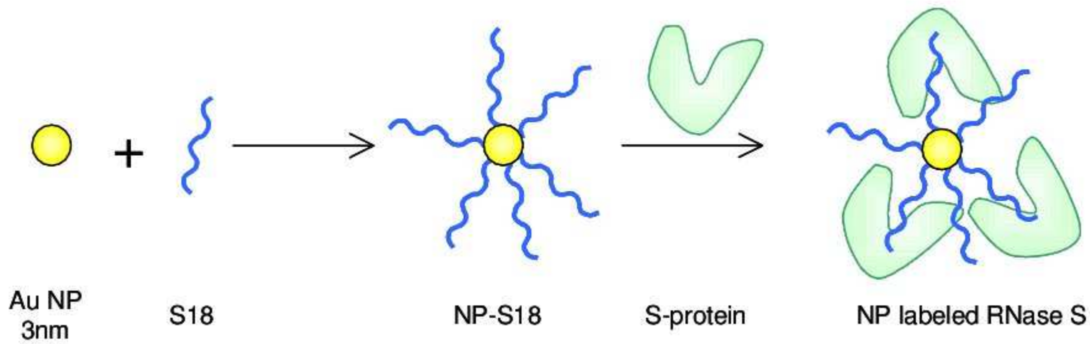
This approach reduced errors by greater than a factor of 15 relative to conventional gene synthesis techniques, yielding DNA with one error per 10,000 base pairs, and can be iterated for greater fidelity. To create custom microarrays, semiconductor photoelectrochemistry was used for in-situ DNA synthesis [Chow, 2008]:



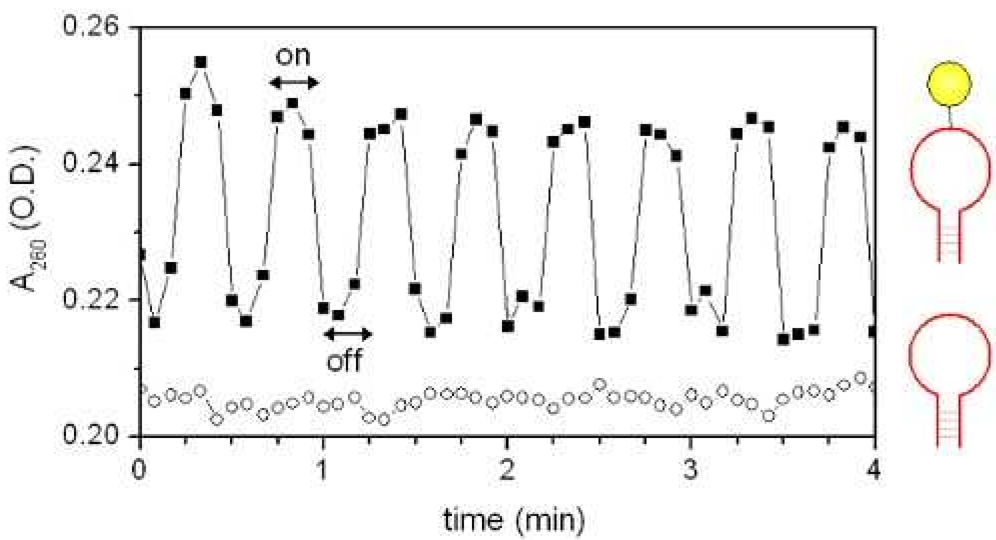




For programmed control of gene expression, site-specific nanoparticle labels were developed. Gold nanoparticles were covalently bonded to a peptide (S18), which self-assembles with the S-protein to form a functional RNase S complex [Park *et al*., 2004; Audin *et al*., 2005]:

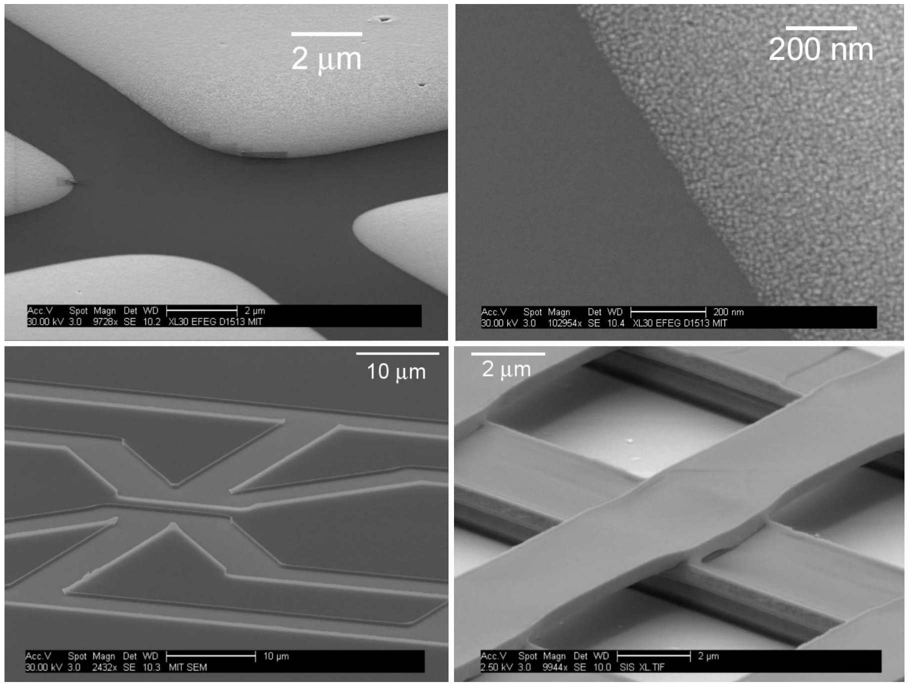


Under radio-frequency irradiation such a gold nanoparticle label was shown to reversibly switch the hybridization and hence functionality of an attached DNA hairpin loop, here observed by the UV absorbance [Hamad-Schifferli *et al*., 2002]:

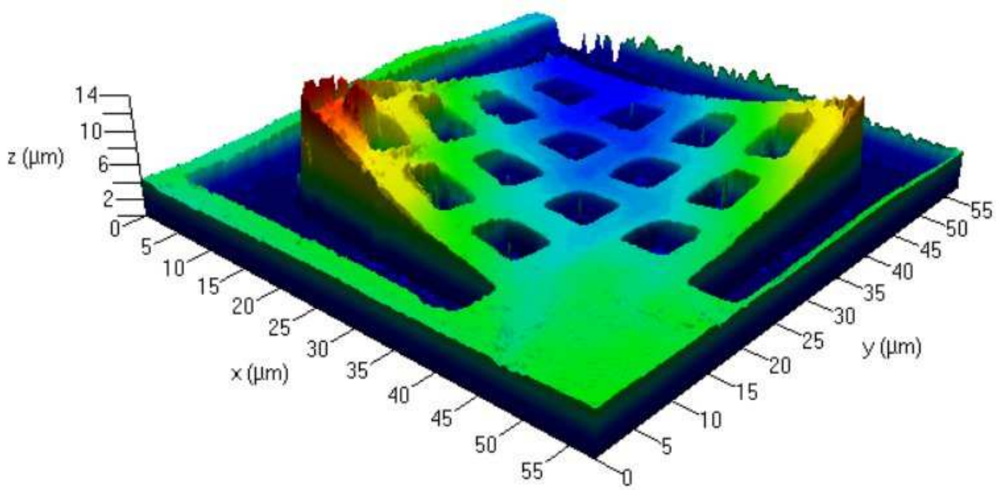


Nanoparticles and proteins were conjugated to quantify their interface, and exploited to control the folding properties of proteins [Aubin-Tam and Hamad-Schifferli, 2005].

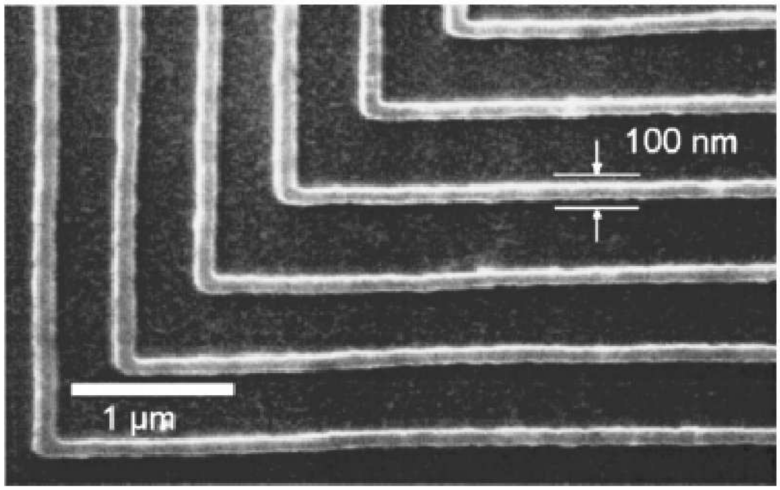
For additive patterning of nanoparticles, an offset liquid embossing process was developed. This transfers patterned material from a polydimethylsiloxane surface of tuned wettability to a rigid or flexible substrate. The printing is fast (seconds), can be done under ambient conditions, and multiple layers can be aligned and printed without the need for planarization [Wilhelm and Jacobson, 2004]:



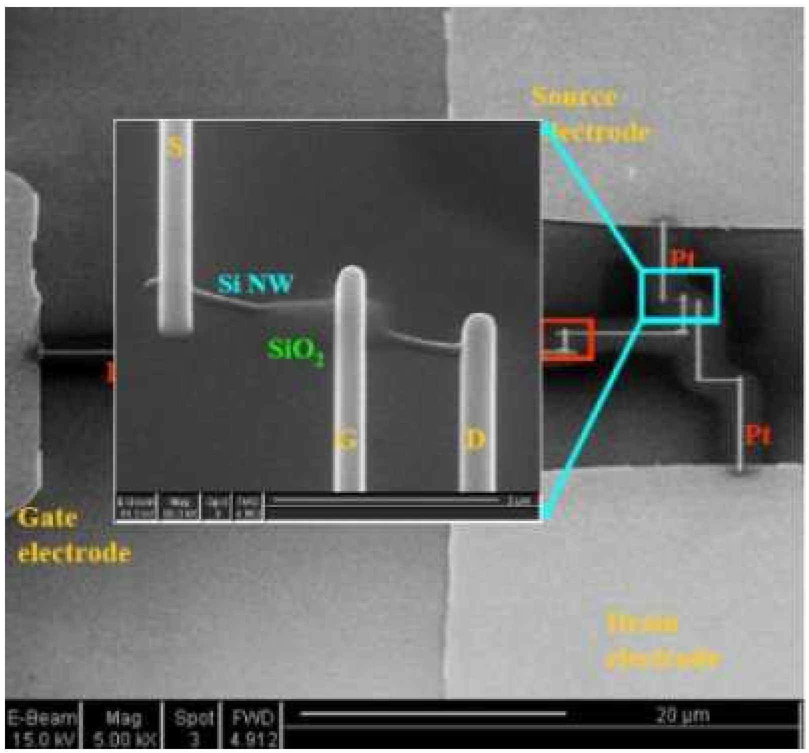
The offset liquid embossing process was used to print micro-electromechanical systems, here producing electrostatic actuators for light modulation (imaging the displacement with CBA's confocal microscope) [Wilhelm *et al.*, 2004]:



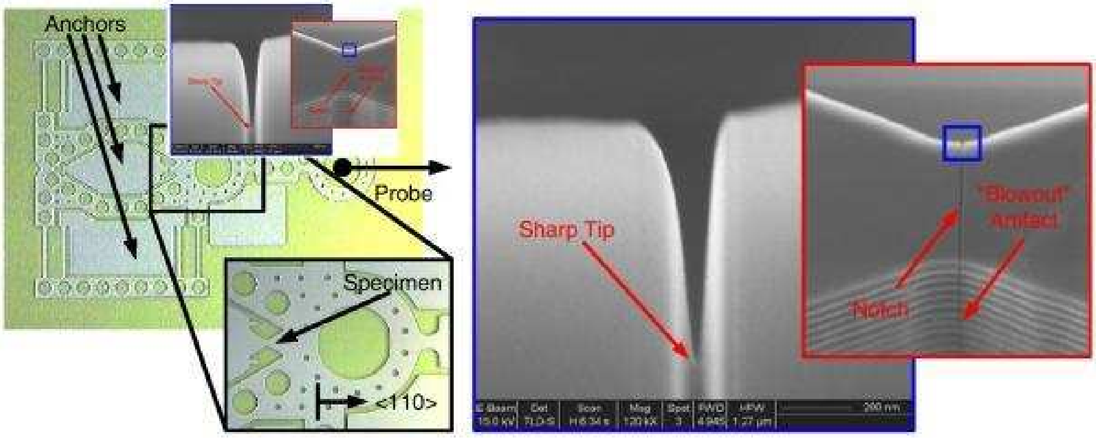
For finer features, CBA's Focused Ion Beam writer (FIB) was used to directly pattern organometallic nanoparticles to produce nanometer-scale wiring:



showing the highest demonstrated throughput for a direct-write process utilizing organometallic precursors [Kong *et al*., 2004], and CBA's e-beam writer was used with the FIB to fabricate field effect transistors from semiconducting nanowires [Joo *et al*., 2007]:

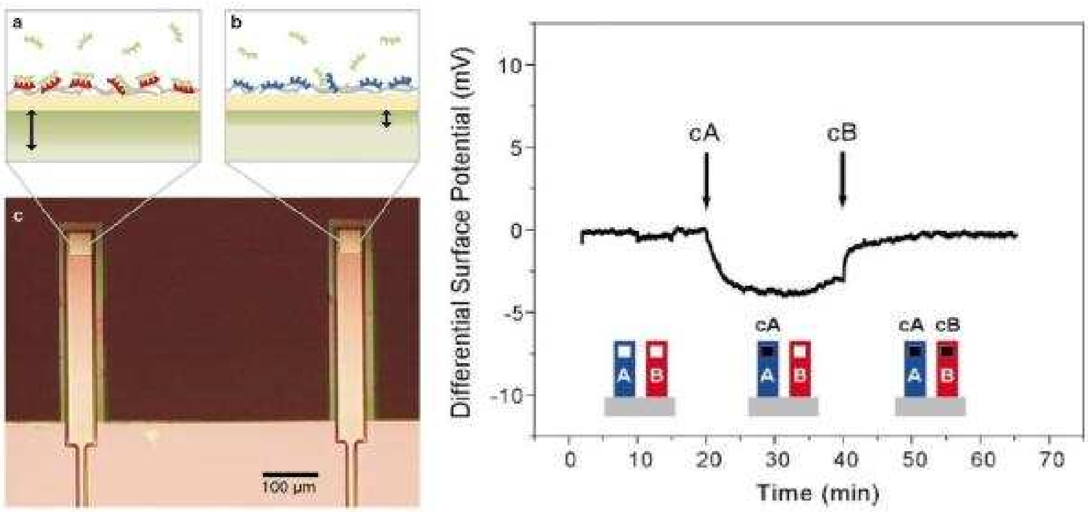


CBA's FIB was also used to notch a SOI substrate that was then fractured at that interface to create a controllable atomically-flat gap:

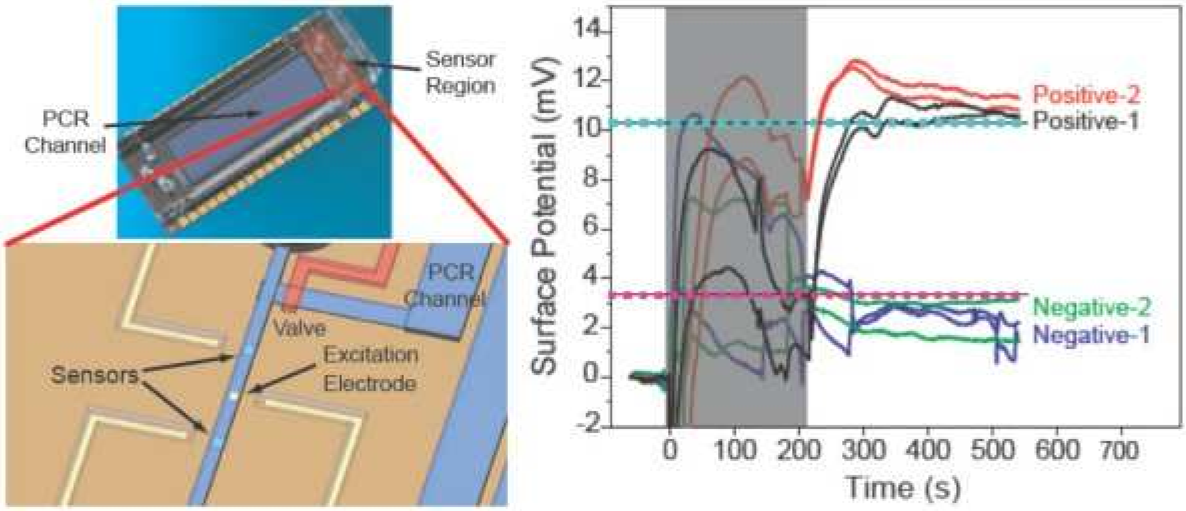


that can be used as a molecular-scale valve [Sprunt and Slocum, 2005]; variable microscale gaps were also used for calibration-free complex impedance spectroscopy of liquids and gases [Ma and Slocum, 2006; Ma *et al.*, 2007].

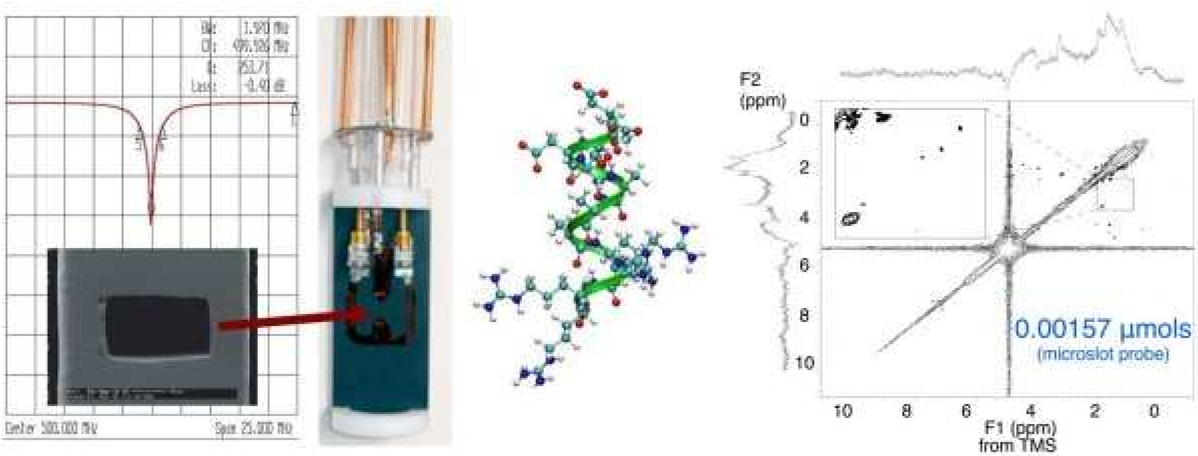
Molecular detection was shown by a field-effect sensor for electronic readout of DNA hybridization. The charge per base at the sugar-phosphate backbone extends the size of an underlying depletion region in the device, shown here differentially detecting an oligonucleotide [Fritz *et al.*, 2002]:



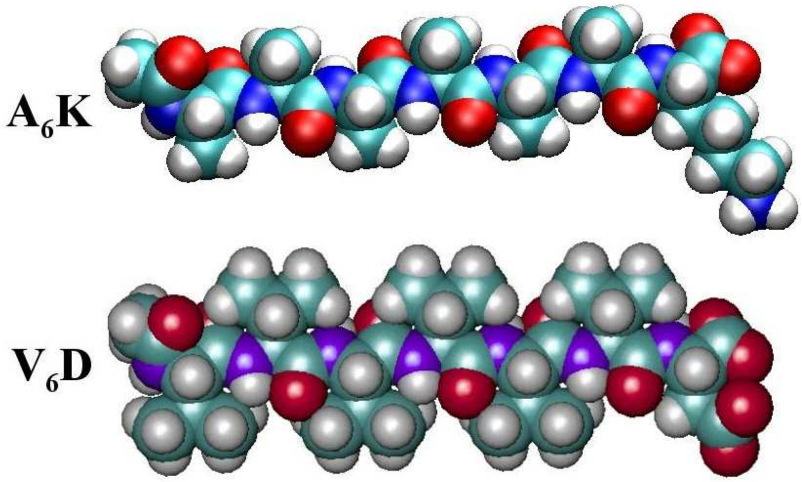
A suspended microchannel resonant mass sensor provided microfluidic integration and significantly reduced ambient damping for such functionalized silicon surfaces [Burg and Manalis, 2003], and an integrated tunneling tip and interferometric sensor provided coherent noise cancellation [Sparks and Manalis, 2004]. Measurement of amplicon intrinsic charge was integrated with resistive heaters, temperature sensors, and microfluidic valves for label-free nucleic acid amplification and detection [Hou *et al.*, 2007]:



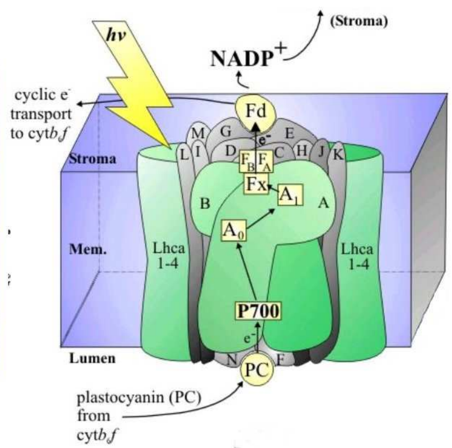
For molecular structural studies, CBA's excimer laser micromachining system was used to fabricate a slot antenna in a microstripline that creates an impedance-matched discontinuity that locally converts RF energy to a strong homogeneous magnetic field. This has demonstrated the best reported sensitivity for an integrated spin-resonance probe, here showing the two-dimensional spectra obtained from a picomolar sample of an acetyl-amide peptide [Maguire *et al.*, 2007]:

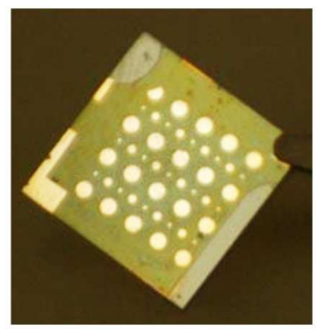


Molecular devices were developed based on the functionality that is available in membrane proteins. Peptide surfactants were synthesized to solubilize, stabilize and crystallize membrane proteins so that they can be used outside of a cell [Yang, 2004]:



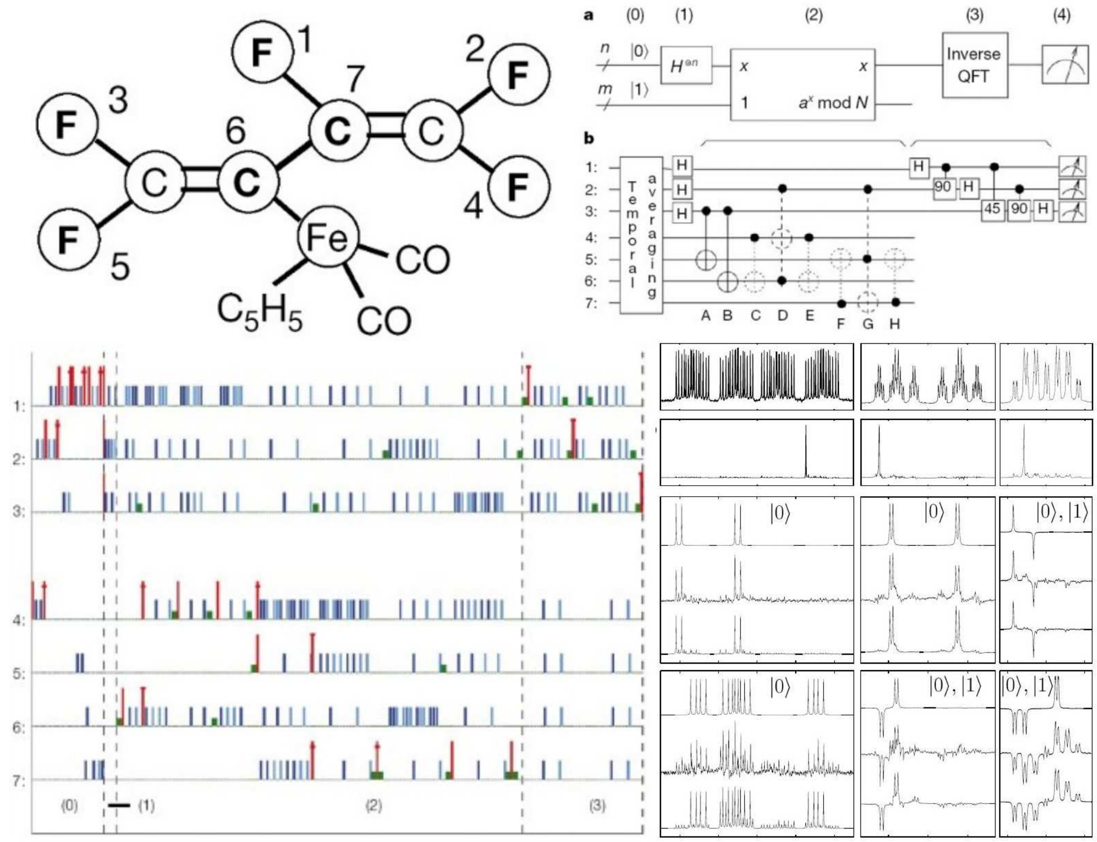
These were used to retain the functionality of the photosystem 1 (PS1) complex (from spinach) on a transparent conducting surface [Kiley *et al*., 2005]:



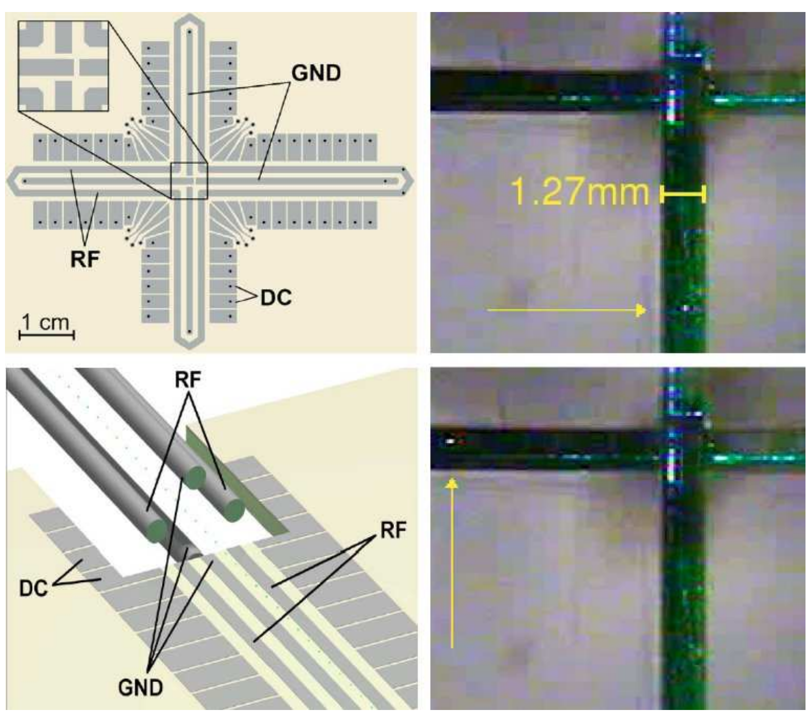


Carbon nanotubes were then used for electron capture from the PS1, to create a photosynthetic photovoltaic device [Das *et al*., 2004].

For molecular computation, CBA support contributed to the development of techniques based on nuclear magnetic spin resonance [Gershenfeld and Chuang, 1997; Vandersypen and Chuang, 2004] that led to some of the earliest and largest quantum computations to date. Following the initial implementation of quantum searching [Chuang, Gershenfeld, and Kubinec, 1998], these include adiabatic optimization [Steffen *et al*., 2003], and factoring [Vandersypen *et al*., 2001], here showing the 7-qubit molecule (a perfluorobutadienyl iron complex), circuit, pulse sequence, and spectra for Shor's algorithm:

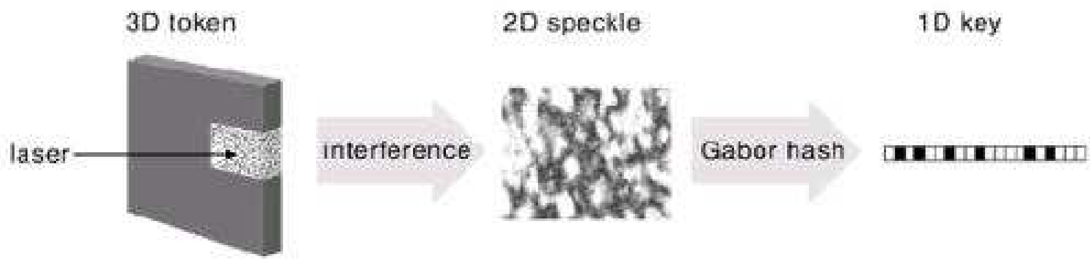


Pulse sequences developed for computing with nuclear spins were subsequently applied to ion trap quantum computers, [Guide *et al*., 2003], and investigation of their scaling resulted in the experimental realization of a planar ion trap array [Pearson *et al*., 2006], showing loading from a conventional linear Paul trap, linear ion movement, splitting and joining of ion chains, and movement of ions through intersections:

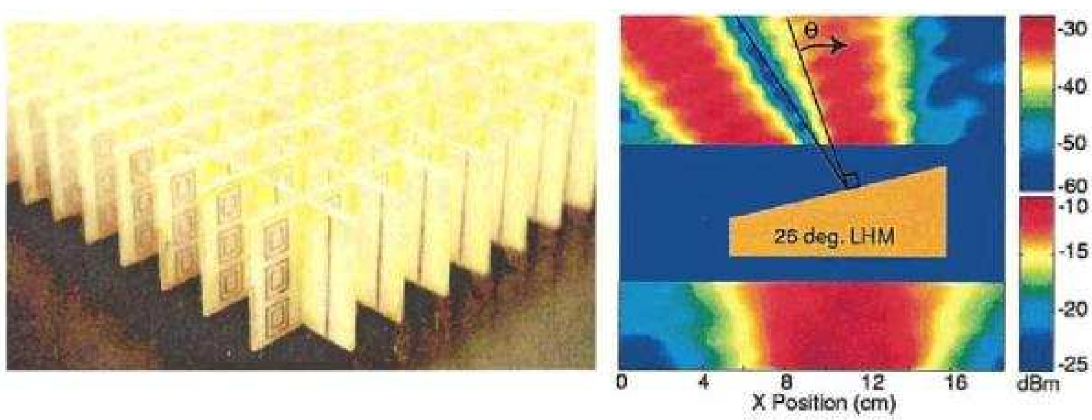


Beyond computation, CBA researchers are applying concepts from quantum information to problems ranging from the study of materials [Lloyd, 2008] to quantum gravity [Lloyd, 2006] and the computational capacity of the universe [Lloyd, 2002]. Results include an interferometric measurement of the phase coherence of dark states in Electromagnetically Induced Transparency (EIT) [Murali *et al.*, 2004], beating the standard quantum limit in a positioning system such as GPS by viewing it as a distributed computation [Giovannetti, Lloyd, and Maccone, 2004], and analyzing the escape of quantum information in the Hawking radiation from a black hole [Lloyd, 2004].

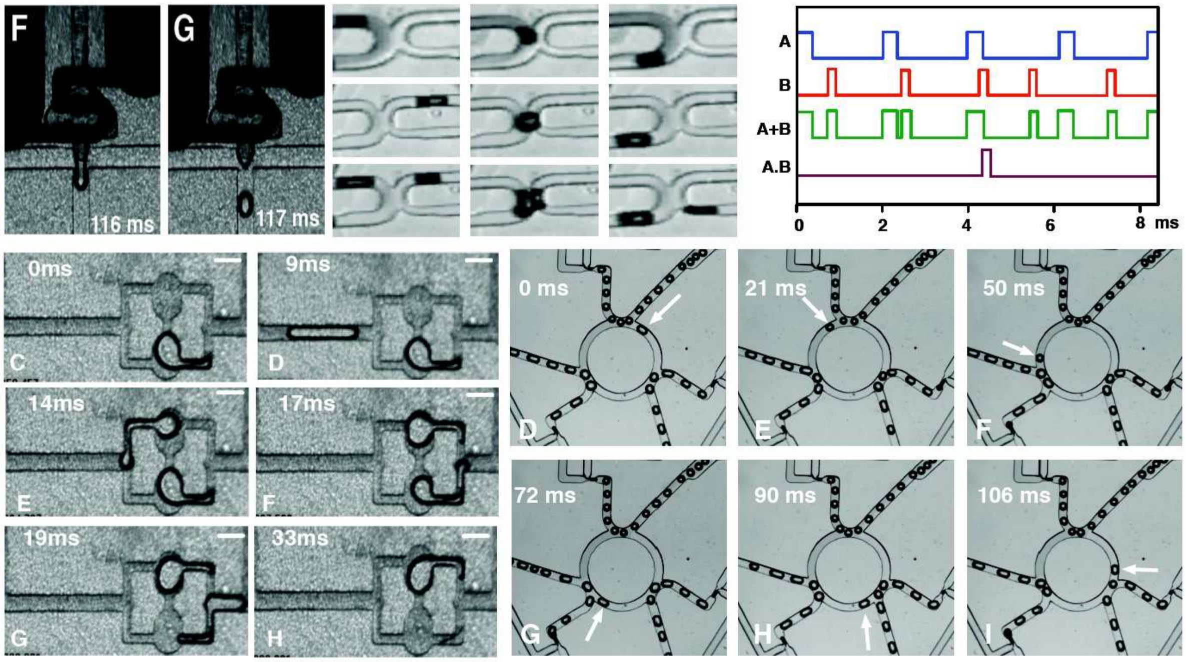
CBA's investigation of the transformation of information in physical interactions has led to advances in coherent classical as well as quantum mechanisms. A new approach to information security came from introducing a physical one-way cryptographic function by showing that photon scattering from inhomogeneous materials in the mesoscopic limit is equivalent to a one-way hash of the scattering structure [Pappu *et al.*, 2002]:



And CBA's fabrication facilities were used in the first measurement of the two-dimensional electromagnetic scattering profile of the focusing inside and outside of a negative-index material [Houck *et al.*, 2003; Brock, 2004]:

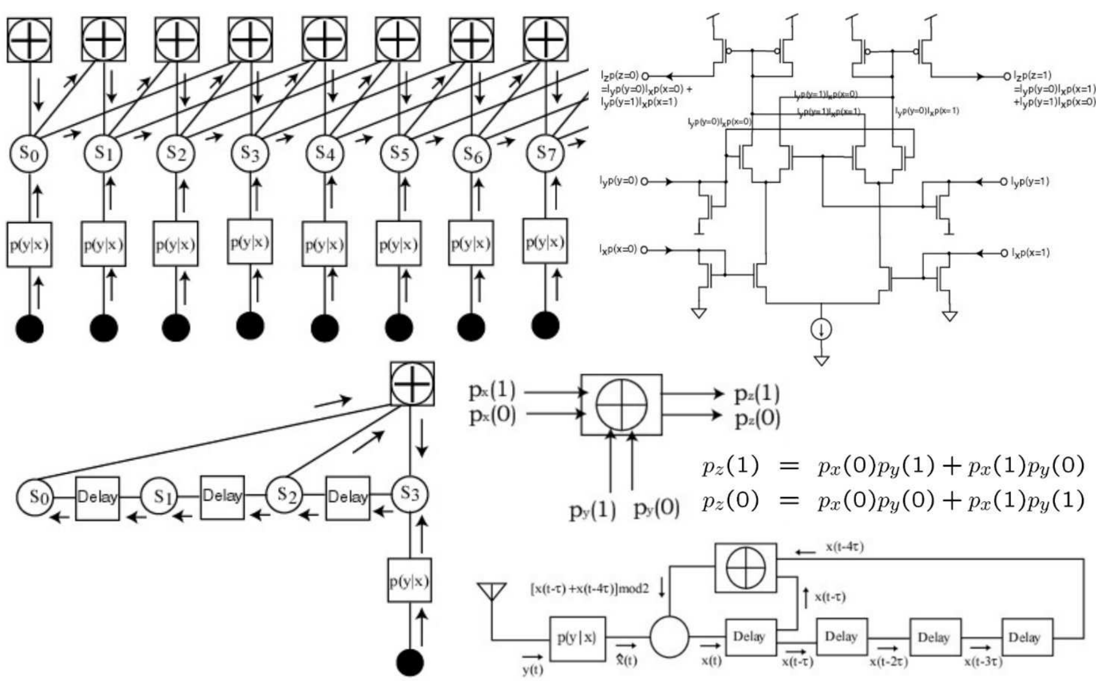


The study of the integration of computation into materials led to the invention of "bubble logic", using two-phase flows in microfluidic channels to simultaneously transport materials and perform logic on them, here showing bubble generation, logic, bistability, and a ring oscillator
[Prakash and Gershenfeld, 2007]:

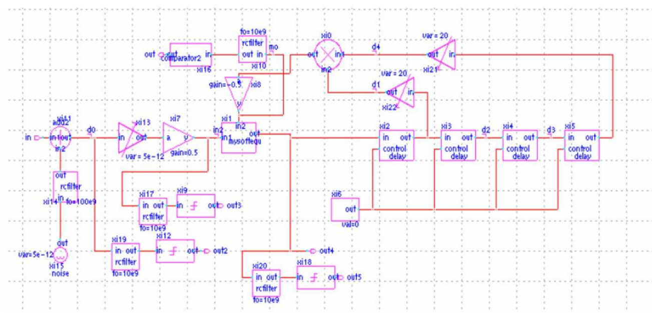


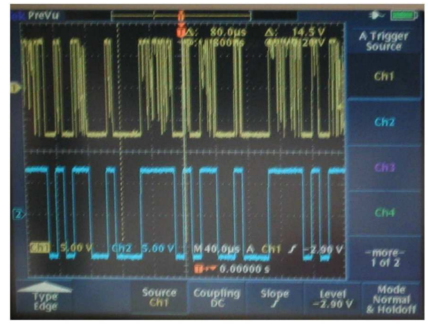
Capillary ratchets that can clock microfluidic circuits were discovered from studying the foraging mechanisms of shorebirds [Prakash et al., 2008].

CBA's studies of these microscopic means for manipulating information promise to lead to the creation of macroscopic systems of unprecedented complexity. Along with investigating the foundations of computation and fabrication, a number of CBA projects are exploring design principles and engineering practice appropriate for this limit of enormous complexity. An emerging programming model is based on "mathematical programming," compiling problems posed as a mathematical program (goals with constraints) into distributed dynamics by message-passing algorithms on the graphical structure associated with sparsity in the primal and dual problem statements. This approach was applied to spread-spectrum carrier acquisition and tracking:



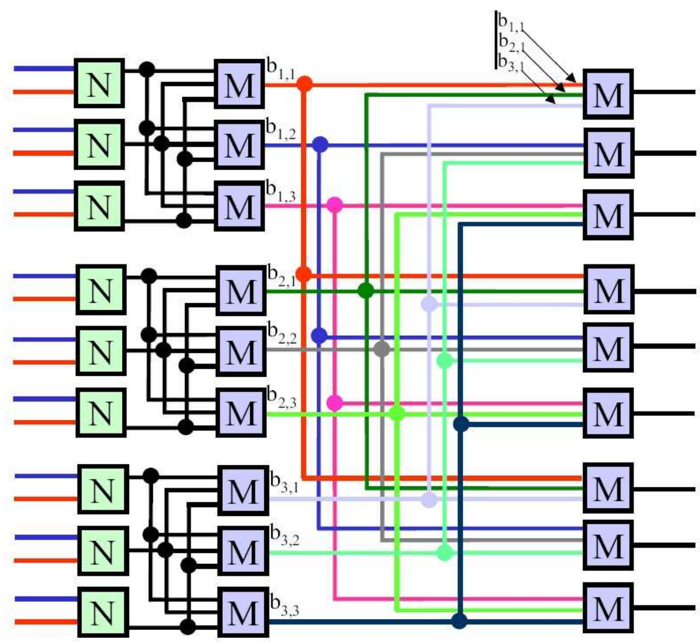
to create a Noise-Locked Loop (NLL) as a generalization of Phase-Locked Loops (PLLs) to coded waveforms [Vigoda, 2003; Vigoda *et al*., 2006]. An NLL circuit was implemented, here compared to simple bit-discrimination on a noisy signal:



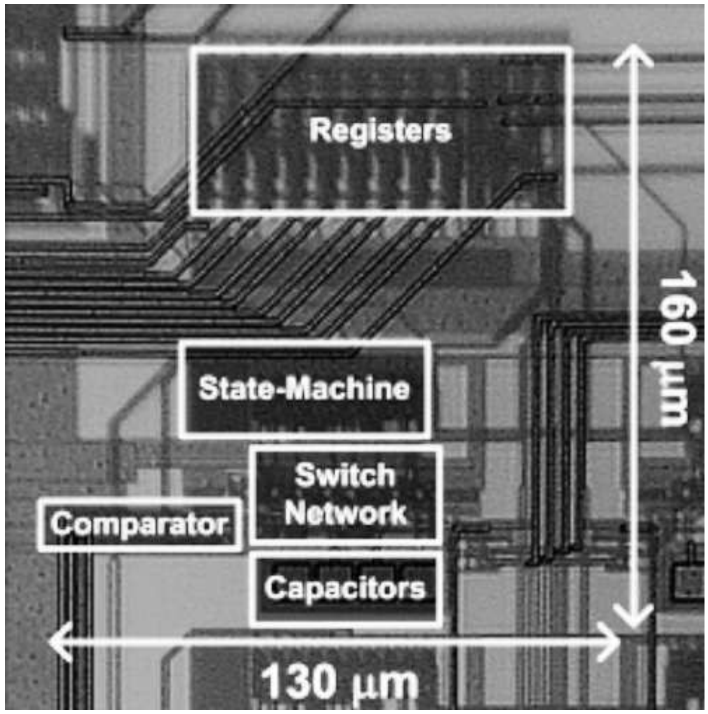


This "analog logic" circuit operates in the state-space of the corresponding digital system but uses a continuous log-likelihood voltage representation that takes advantage of the available device degrees of freedom.

A related project has taken early ideas about fault-tolerant computers that have since been developed for quantum computing and applied them back to classical logic, showing that fault-tolerant designs can improve the reliability and resource efficiency of classical circuits [Impens, 2004]:



Other work on electronics that operates between analog and digital limits has included the development of an ultra-low-leakage analog storage cell [O'Halloran and Sarpeshkar, 2004], spike-based signal processing [O'Halloran and Sarpeshkar, 2002], and a time-based analog-to-digital converter inspired by the operation of spiking neurons:

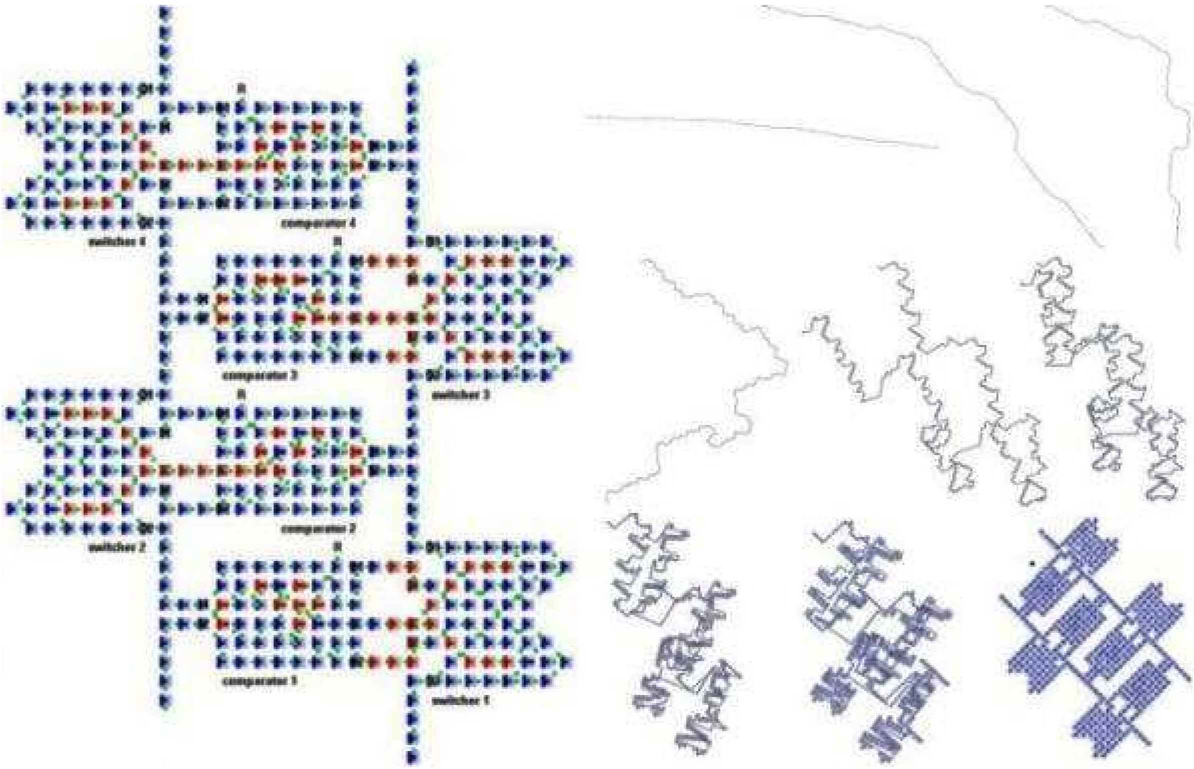


offering the first conversion time that scales linearly rather than exponentially with bit precision, and the highest reported A/D energy efficiency [Yang and Sarpeshkar, 2006].

Computation in distributed systems was investigated in the context of "paintable" computing, seeking to turn computation into an extensible raw material by fabricating enormous numbers of simple devices that can solve global problems through their local interactions. To guide scaling to silicon, a programming model for a paintable computer was implemented in a pushpin system, taking as a test problem distributed graphical rendering in a statistical display medium:

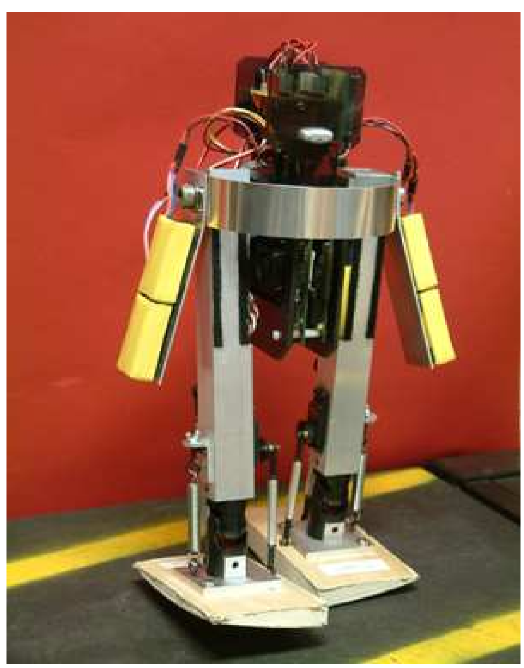
 

[Butera, 2002], and a similar system was used to study distributed localization [Broxton *et al.*, 2005]. The physical constraints on distributed computation were reflected in the development of conformal computing substrates [Gershenfeld, 2008] based on asynchronous logic automata [Dalrymple, 2008] assembled by coded folding [Cheung *et al.*, 2008]:

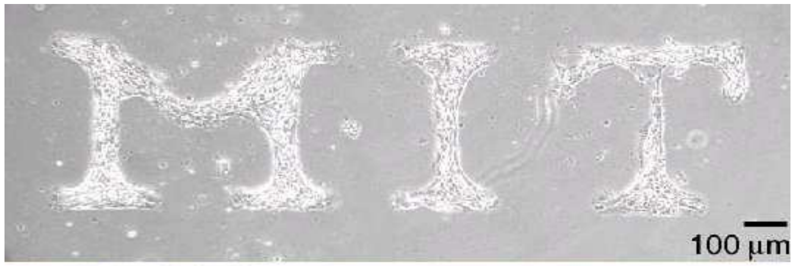


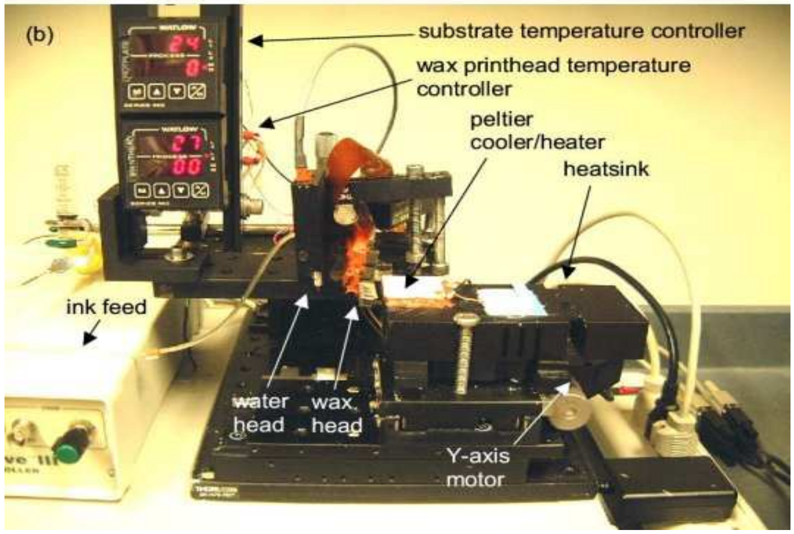
Current work is extending this architecutre to develop analog logic automata chips for reconfigurable mixed-signal and statistical processing.

Investigation in CBA of the connection between computational and physical dynamics resulted in the development of a dynamically stable bipedal robot that learns to walk in 20 minutes [Tedrake, 2004; Collins *et al*., 2005]:

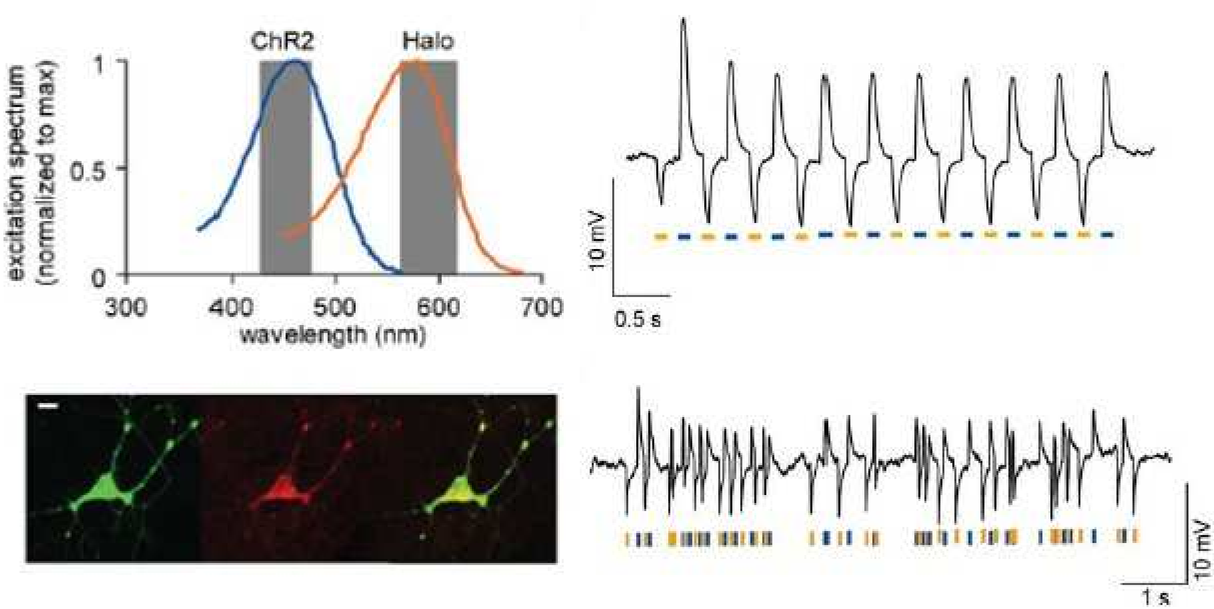


Current work is extending the online learning algorithms to more complex mechanical systems and terrains [Byl and Tedrake, 2008]. The relationship between mathematical and physical mechanisms for learning is also being investigated at the cellular level, including the development of a printing process to pattern networks of neurons and glia cells [Sanjana and Fuller, 2003]:





CBA facilities were used to develop the first-ever method for silencing neural activity with light [Han and Boyden, 2007]:



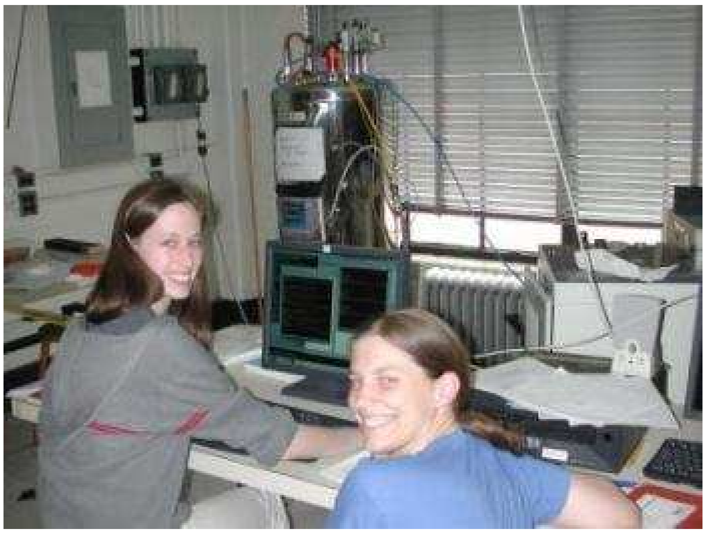
and to make arrays for optically switching on and off 3D brain circuits [Bernstein *et al.*, 2008]. These studies of learning in biological systems are closely connected to CBA's investigation of mathematical programming in engineered systems, which is seeking to forward- rather than reverse-engineer the biological principles underlying the use of local interactions to solve global problems [Lafuente and Gershenfeld, 2008].

3. **Describe the opportunities for training and development provided by your project.**

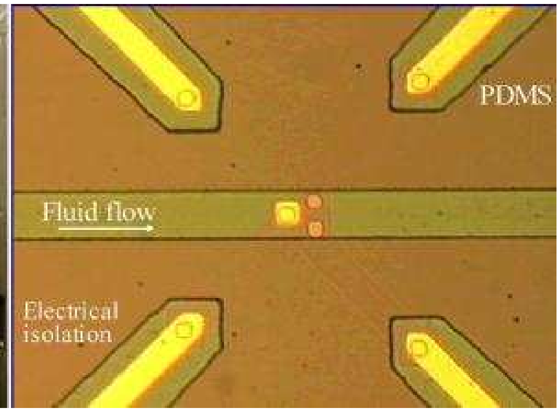
CBA has directly supported about 100 grad and undergrad students and indirectly contributed to training about 200 students (with two subsequently joining MIT's faculty), working with a unique experimental resource developed to provide input and output across 9 orders of magnitude:

A popular rapid-prototyping class was developed to provide instruction in its integrated use, MAS.863: How To Make (almost) Anything. Other classes that have been developed with direct and indirect CBA contributions include:

- hands-on training in quantum computing in 8.13: Experimental Physics



- rapid-prototyping of microstructures in 6.151: Semiconductor Devices Project Laboratory



- 4.206: Introduction to Computing
- 4.212: Design Fabrication
- 4.173: Design Fabrication Workshop
- 6.971: Engineering Simple Biological Systems
- 7.86, BE.481, MAS.866: Fundamental Limits of Biological Measurement
- 8.371J, MAS.865J: Quantum Information Science
- BE.309: Biological Engineering II: Instrumentation and Measurement
- BE.442: Molecular Structure of Biological Materials
- MAS.862: The Physics of Information Technology
- MAS.864: The Nature of Mathematical Modeling
- MAS.961: How To Make Something That Makes (almost) Anything

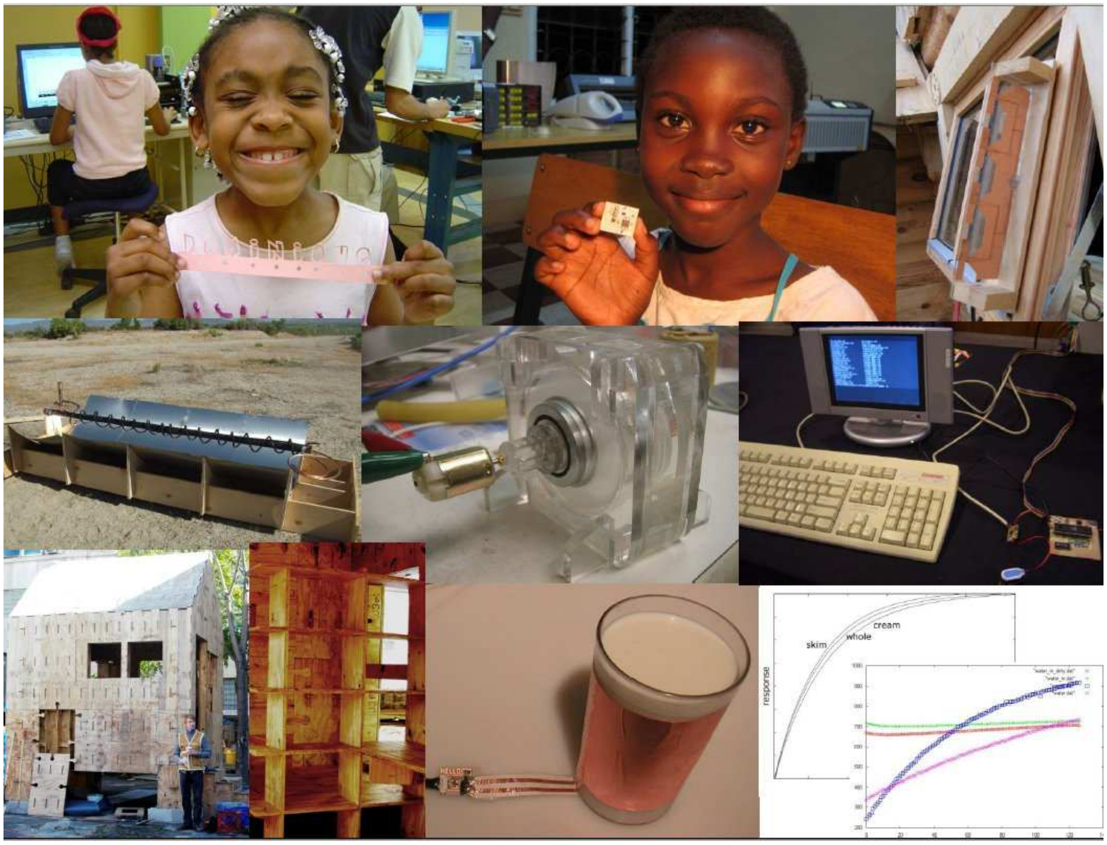
CBA's educational activities have expanded beyond campus, through activities in the field fab lab network including a 10 module "FabKidz" curriculum aimed at 6th-8th grade school children that was developed and administered by a 15-year-old fab lab participant (who's been working in a fab lab since she was 12) [Millner and Daily, 2008]:

and a NSF grant (0802388) to the Midwest Fab Lab Network to integrate and analyze the impact of digital fabrication in community college curriculum.

4. **Describe outreach activities your project has undertaken.**

The focus of CBA's outreach activities has been a growing network of field "fab labs":

[Gershenfeld, 2005]. Rather than just communicating research results, fab labs provide access to prototype tools for personal fabrication in underserved communities around the world, allowing ordinary people to create as well as consume technology. Fab lab activities range from technological empowerment to informal project-based peer-to-peer technical training, to local problem-solving, to small-scale high-tech business creation, to grass-roots research and development; projects include high-gain antennas for mesh wireless networks, low-cost locally-produced thin-client computers, instrumentation for environmental, agricultural, and medical measurements, wind, water, and steam turbines, and rapid-prototyping of housing:



Fab labs have spread in the US from inner-city Boston to the Midwest to San Diego and the South Bronx, in Europe from the north of Norway to Barcelona and the Netherlands, in Africa from Ghana to South Africa to Kenya, to India, and (with supplemental NSF support) Afghanistan. CBA supports these labs with communications infrastructure (including hosting a broadband videoconference), by managing shared inventory and capabilities, and developing projects and processes (with an ultimate aim of a fab lab being able to make a fab lab).

Fab lab sites include formal and informal institutions, community centers and community colleges, farms and studios. Financial support, initially from CBA, has expanded to include other philanthropic sources (such as a MacArthur Foundation award to the South Bronx fab lab) and government sources (such as South Africa's national fab lab network). This response has been matched by public and press interest, with features in media including *The Economist*, *USA Today*, *NPR*, *BBC*, and *CNN*.

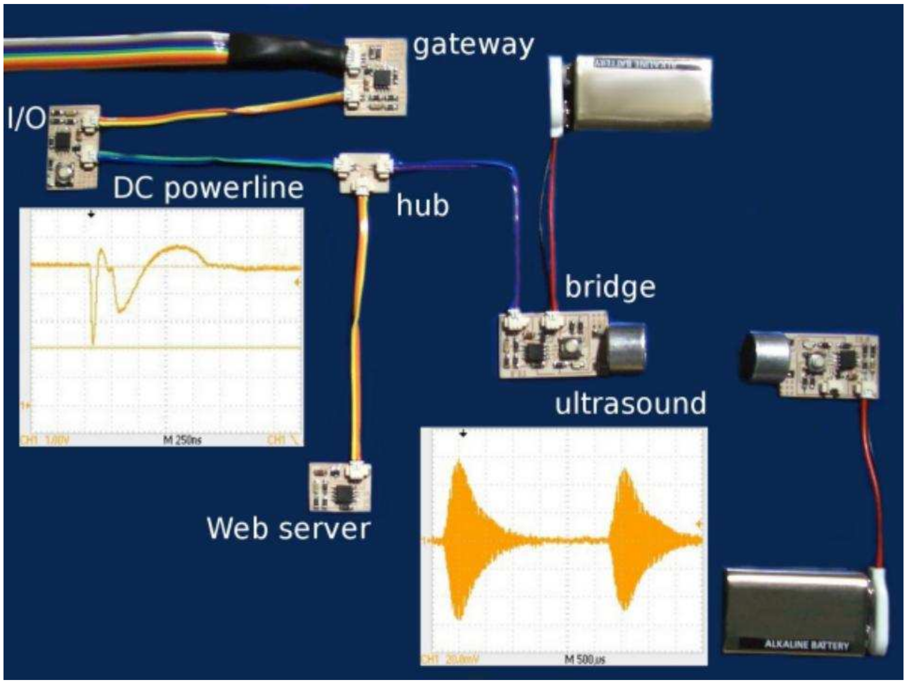
To keep up with the growth of fab labs, an independent non-profit Fab Foundation is being launched to support invention as aid, a for-profit Fab Fund to help global capital reach local inventors and local inventions find global markets, and a Fab Academy to provide distributed advanced technical education in principles and applications of digital fabrication. The emergence of these organizations can be understood as an ultimate impact of the work of CBA and its partners. Bringing together computer science and physical science has led to the development of digital fabrication, in turn enabling personal fabrication. And the availability of prototype tools for personal fabrication is allowing anyone anywhere to be able to make almost anything. Combined with video networks and online libraries, this means that previously scarce resources of advanced research and educational institutions can become much more widely distributed and broadly accessible.

Since 2004 CBA has co-organized an annual global gathering of the field fab lab and digital fabrication research communities, co-hosted in 2007 with NSF and the Department of Energy: http://cba.mit.edu/events/07.08.fab/. A mobile fab lab was developed for this event, here shown at Chicago's Museum of Science and Industry:

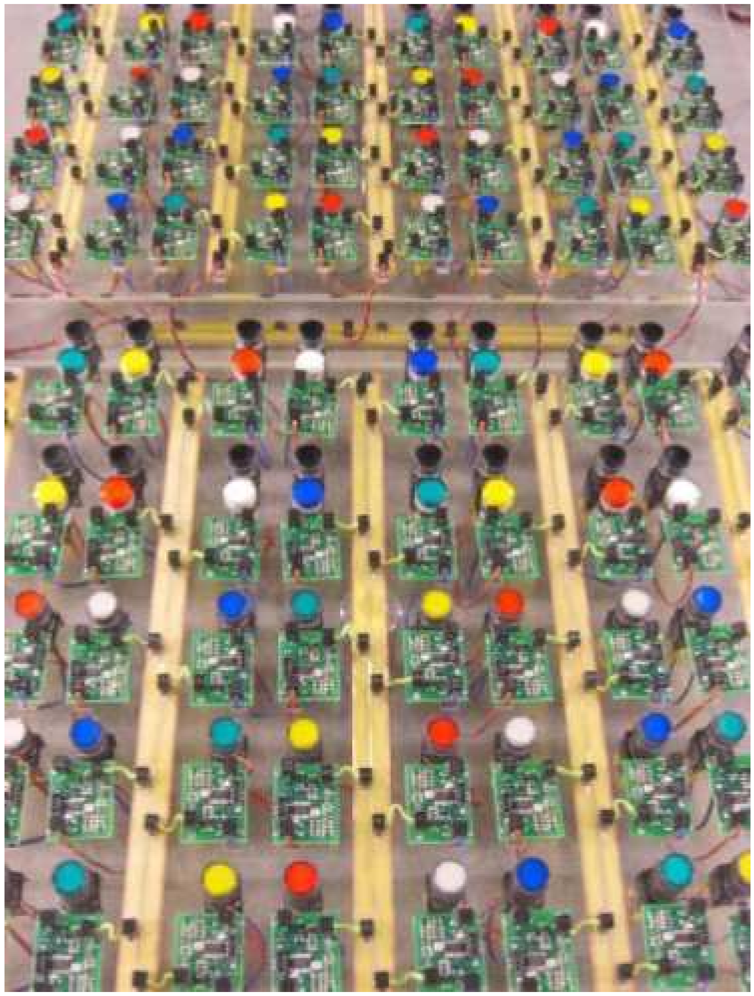
Such topical meetings targeting emerging research areas have been an important component of CBA's outreach within the scientific community. These have included meetings on *Coding and Computation in Microfluidics* [http://cba.mit.edu/events/07.05.fluid/], *Energy and Computation: Flops/Watt and Watts/Flop* [http://cba.mit.edu/events/06.05.energy/], *Digital Fabrication* [http://cba.mit.edu/events/06.06.ZA/symposium.html], *Avogadro-Scale Engineering* [http://cba.mit.edu/events/03.11.ASE/], *Quantum Information Processing* [http://cba.mit.edu/events/05.01.QIP/]

and *Internet 0* [http://cba.mit.edu/events/04.09.I0/]. The latter gathered original Internet architects as well as current counterparts, and industrial partners. At the meeting a parallel was seen between the early days of the Internet and embedded networking today, with Internet 0's time-domain impulse-response encoding:

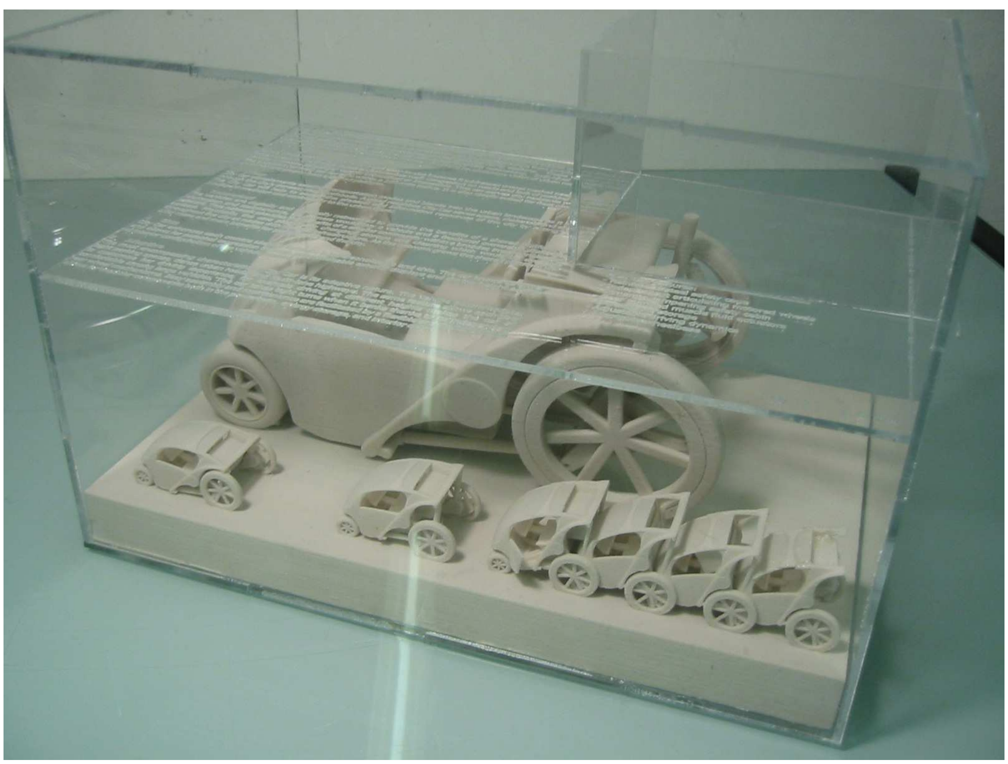
providing end-to-end modulation to enable interdevice internetworking:



[Gershenfeld *et al*., 2004; Gershenfeld and Cohen, 2006]. A follow-up event on energy applications [http://cba.mit.edu/events/07.05.energy/] led to launching a project on Intelligent Infrastructure for Energy Efficiency (I2E), in cooperation with Department of Energy national labs and industrial partners, for large-scale testbeds applying Internet 0 to building energy efficiency:



Another form of outreach has been through projects using CBA's rapid-prototyping facilities. One is a concept car project with Prof. Bill Mitchell, Frank Gehry, and General Motors that is developing an electric one-way share vehicle:



Another is with Drs. Florence Friedman (Brown University) and Walter Gilbert (Harvard University), working with CBA's shop technician John Difrancesco to 3D scan, virtually assemble, and print fragments of antiquities from the collection of Boston's Museum of Fine Arts:



Publications and Products

1. **What have you published as a result of this work?**
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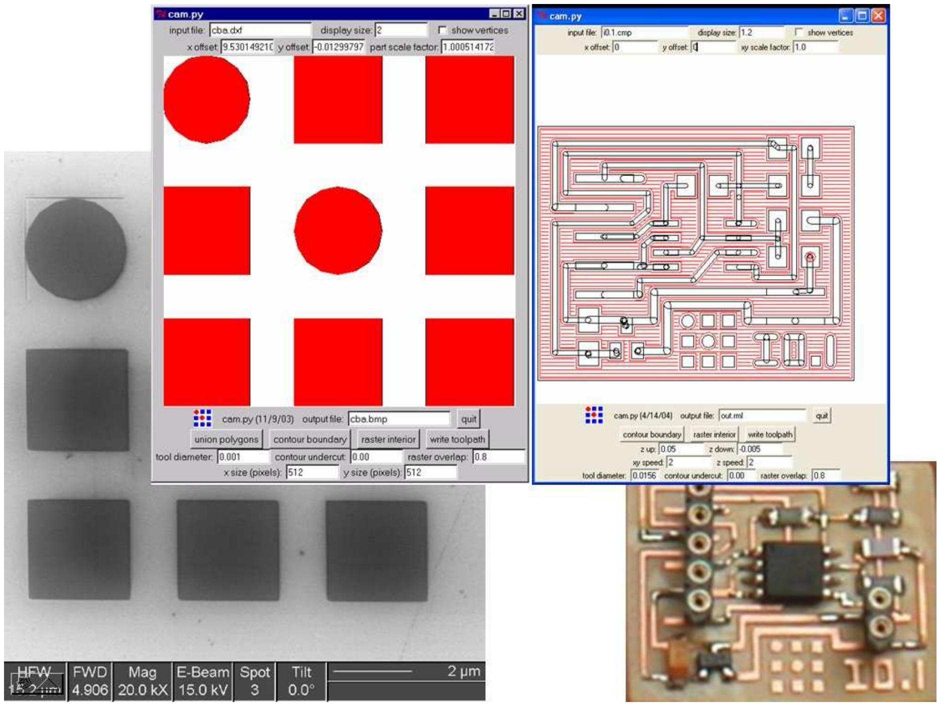
2. **What Web site or other Internet site have you created?**

http://cba.mit.edu/
Primary CBA site

http://fab.cba.mit.edu/
CBA server for fab classes/labs/facilities

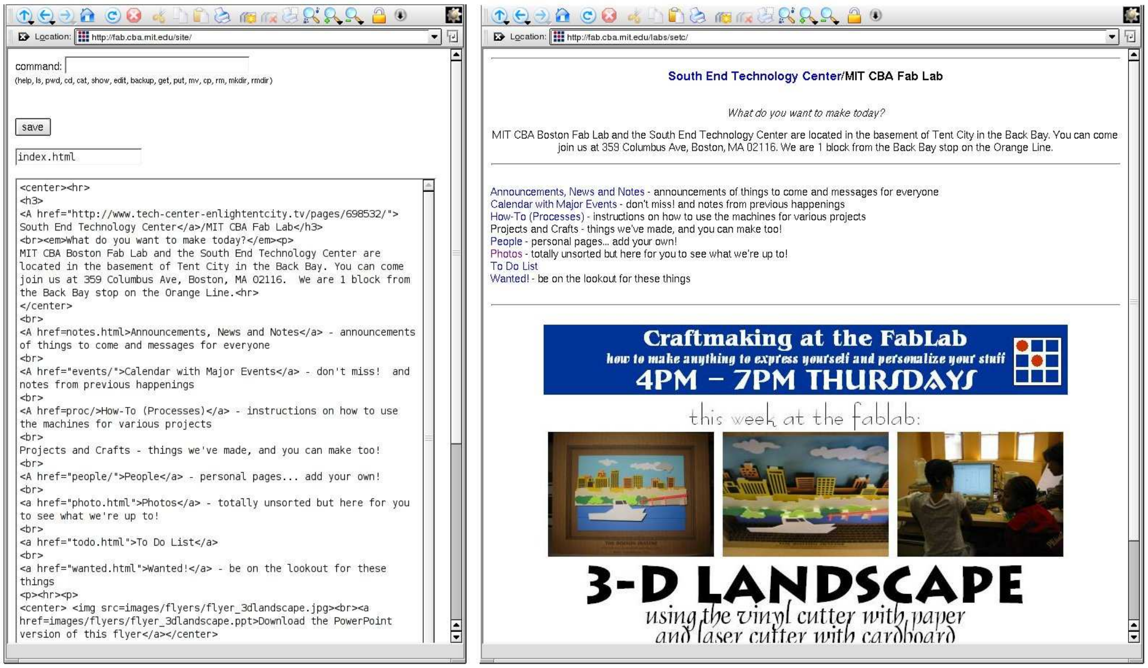
3. **What other specific products (databases, physical collections, educational aids, software, instruments, or the like) have you developed?**

A significant constraint on the use of the fabrication tools in both CBA's on-campus facilities and its field fab labs has been limiting assumptions about their applications that are imposed by the available CAM software. Therefore, in support of the research program a universal CAM tool was written (cam.py) that can currently input SVG, 2D and 3D DXF, Gerber, Excellon, and JPEG design files, and produce output toolpaths for an NC mill, machining center, vinyl cutter, laser cutter, waterjet cutter, excimer micromaching center, and focused ion-beam writer:

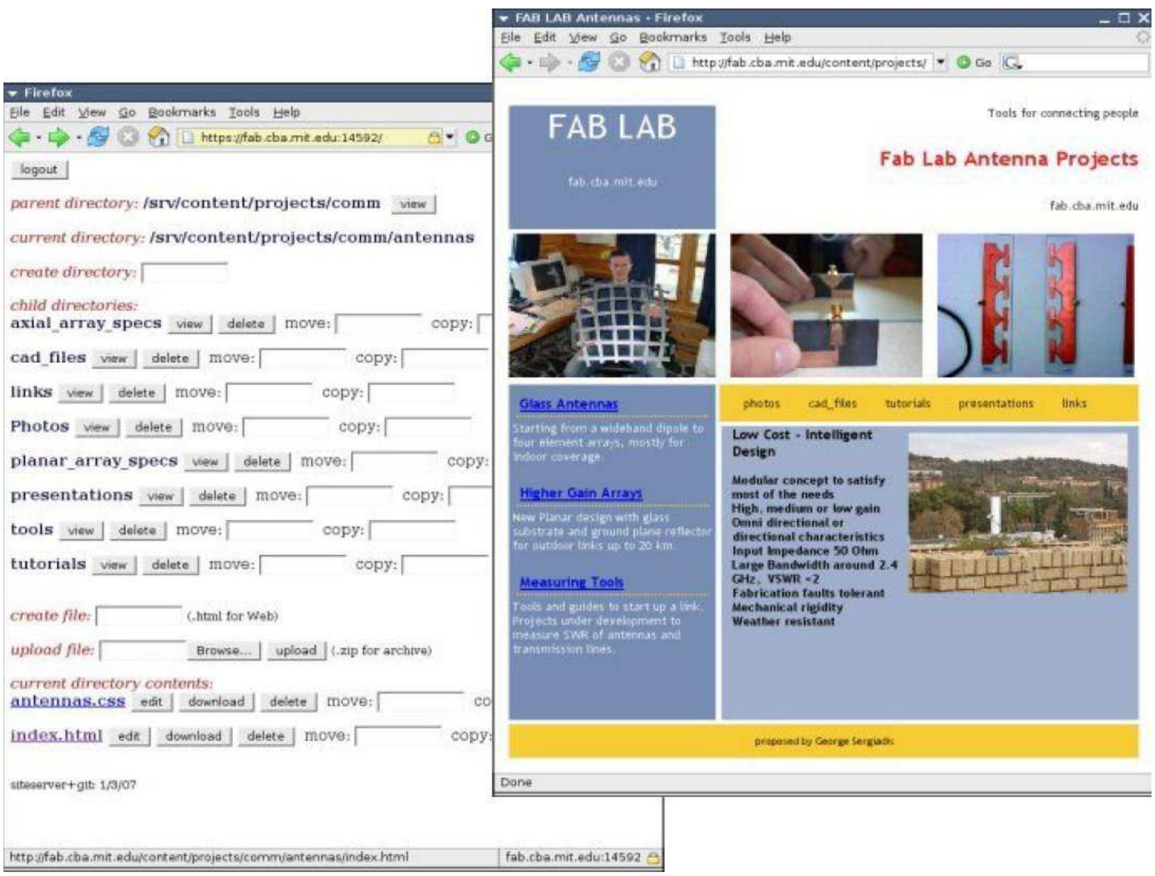


This was followed by a universal design tool, cad.py, based on describing objects with algorithms, represented them by mathematical satisfiability strings, and solving these on a lattice:

Another program (site.py) was written to support project documentation and process knowledge sharing within and across the fab labs, going beyond collaborative Web-site editing to provide in the field on-campus capabilities by exposing a restricted command shell available through a Web interface:

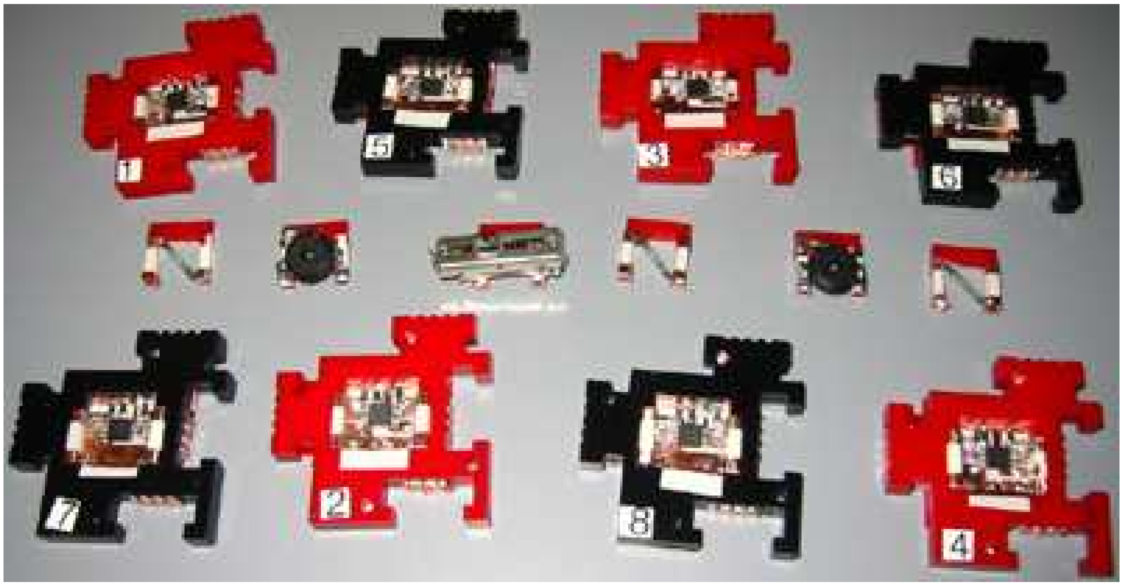


This has grown into a Web interface to a distributed version control and content management system (siteserver.py):



These capabilties are being merged in a third software generation, "kokompe" (named after a district with mechanical repair shops in Ghana), that provides modular thin-client user interfaces communicating with an engineering workflow server for modeling, rendering, toolpath generation, machine control, and distributed project management.

An example of the use of the fab lab hardware and software is the "Scratch Patches," functional building blocks containing embedded sensing, computing, and communications that are made from laser-cut tiles with laminated vinyl-cut circuits, allowing kids to assemble custom devices such as computer game controllers.



[Millner, 2005].