THE CENTER FOR
BITS AND ATOMS
Massachusetts Institute of Technology

Prof. Neil Gershenfeld

Director

http://ng.cba.mit.edu


The Economist

Log in | Register | Subscribe | Digital & mobile | Events | Topics A-Z | Newsletters | Jobs

Friday June 1st 2012

World politics | Business & finance | Economics | Science & technology | Culture | Blogs | Debate | The World in 2012 | Multimedia | Print edition

Current issue | Previous issues | Special reports | Politics this week | Business this week | Leaders | KAL's cartoon | Obituary

3D printing

The printed world

Three-dimensional printing from digital designs will transform manufacturing and allow more people to start making things

Feb 10th 2011 | FILTON | from the print edition

Like 5.4k Tweet 923

Comment (32) | Print | E-mail | Reprints & permissions


HUFF POST BUSINESS

3D Printing: The Most Disruptive Technology Yet?

Posted: 03/08/2013 5:40 pm


NewScientist

search New Scientist | Go | Log in | My New Scientist

Home | News | In-Depth Articles | Blogs | Opinion | TV | Galleries | Topic Guides | Last Word | Subscribe | Dating | Look for Science Jobs

SPACE | TECH | ENVIRONMENT | HEALTH | LIFE | PHYSICS&MATH | SCIENCE IN SOCIETY | Cookies & Privacy

3D printing: Second industrial revolution is under way


THE VANCOUVER SUN

NEWS | OPINION | BUSINESS | SPORTS | ENTERTAINMENT | LIFE | HEALTH | TECHNOLOGY | TRAVEL

3D printing: new mother of invention


The Telegraph

HOME | NEWS | WORLD | SPORT | FINANCE | COMMENT | BLOGS | CULTURE | TRAVEL | LIFE

Politics | Obits | Education | Earth | Science | Tech | Defence | Health | Scotland | Royal

Technology News | Technology Companies | Technology Reviews | Video Games

HOME » TECHNOLOGY

Make your own: the 3D printing revolution

Today you can make plant pots; in the future it could be phones, even houses. But should big business fear the 3D printing revolution?


The Motley Fool. To Educate, Amuse & Enrich

Browse by | Enter Ticker

Welcome to the 3D printing revolution

By Andrés Cardenal - March 29, 2012 | Tickers: DDD, NKE, SSYS | 1 Comment


Sky.com | News | Sports

sky NEWS HD First for Breaking News

SKY NEWS | WEB

3D Printing Revolution Could Re-Shape World


Home | News Viewer | Markets | Investing | Trading Deck | Personal Finance | Retirement | Economy/Politics | Industries | Log In

PRESS RELEASE

March 7, 2013, 8:00 a.m. EST

Industry Experts Are Calling 3D Printing the 'Third Industrial Revolution', That May Change Economies Globally

MarketWatch THE WALL STREET JOURNAL.

March 30, 2013 1:18 PM EDT

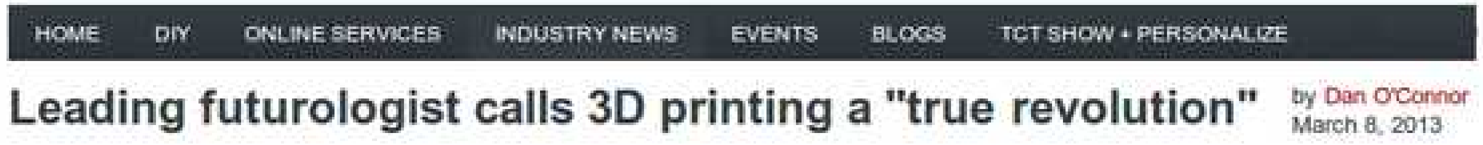
New York Closed | London Closed | Tokyo Closed


USA TODAY | NEWS | SPORTS | LIFE | MONEY | TECH | TRAVEL | OPINION | 58°

3-D printing is revolutionizing product development

PRINTING IN THE THIRD DIMENSION

New printing technology significantly reduces the time corporations spend prototyping fresh designs and now consumer-level machines


HOME | DIY | ONLINE SERVICES | INDUSTRY NEWS | EVENTS | BLOGS | TCT SHOW + PERSONALIZE

Leading futurologist calls 3D printing a "true revolution"

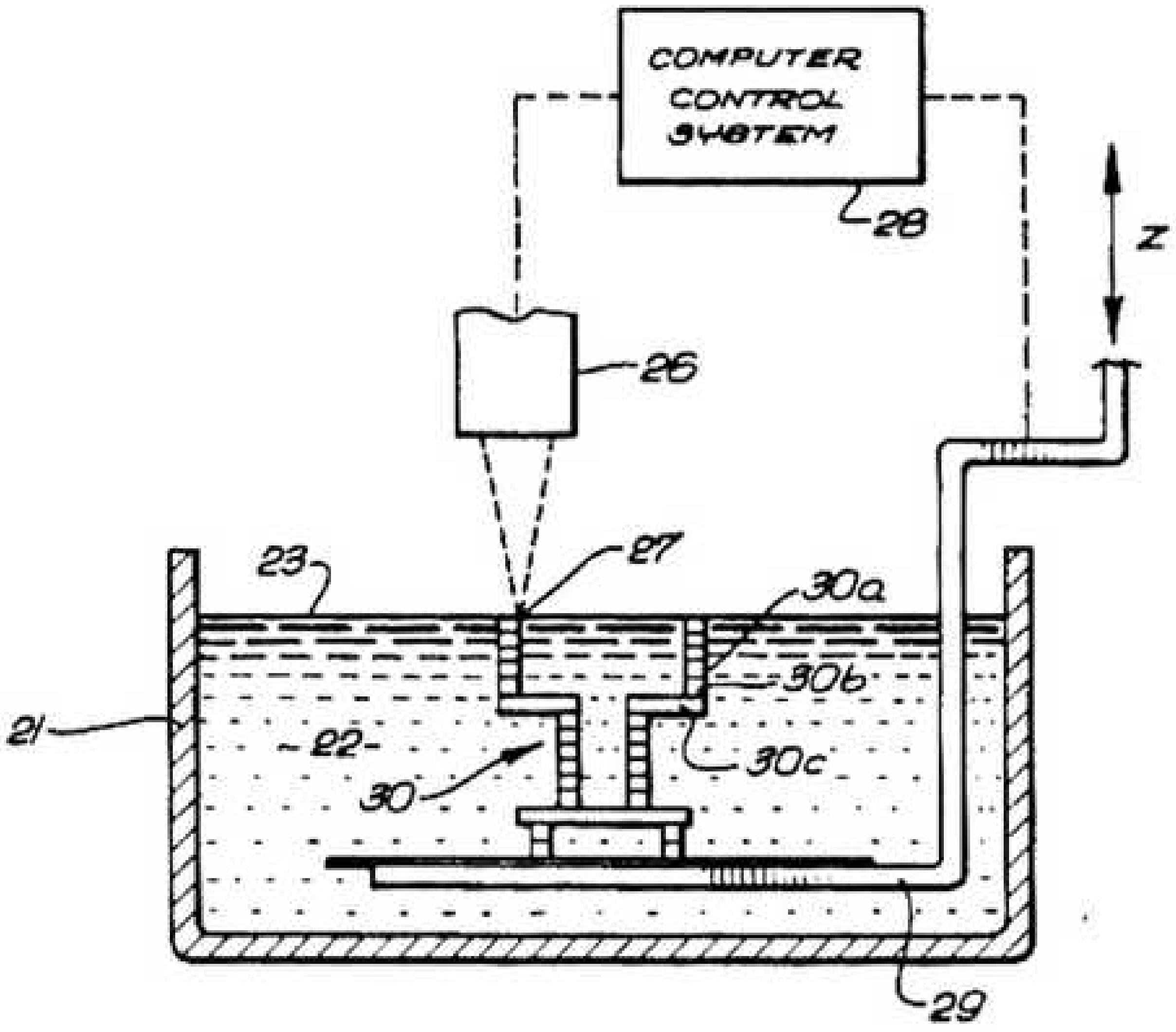
by Dan O'Connor
March 8, 2013


Home | Portfolio | Market Currents | Investing Ideas | Dividends & Income | ETFs | Macro View | ALERTS | PRO

3D Printing: Profiting From The Revolution

Mar 8 2013, 13:17 | about: PRLB

Seeking Alpha^α Read. Decide. Invest.



United States Patent [19]

Hull

[11] **Patent Number:** **4,575,330**

[45] **Date of Patent:** **Mar. 11, 1986**

[54] **APPARATUS FOR PRODUCTION OF THREE-DIMENSIONAL OBJECTS BY STEREOLITHOGRAPHY**

[75] Inventor: **Charles W. Hull**, Arcadia, Calif.

[73] Assignee: **UVP, Inc.**, San Gabriel, Calif.

[21] Appl. No.: **638,905**

[22] Filed: **Aug. 8, 1984**

[51] **Int. Cl.**^{4} **B29D 11/00**; G03C 00/00

[52] **U.S. Cl.** **425/174.4**; 425/174; 425/162; 264/22; 430/269; 156/58; 365/119; 365/120

[58] **Field of Search** 425/162, 174, 174.4, 425/425; 264/22, 183, 40.1; 430/269; 156/38, 58, 275.5; 365/107, 119, 127

[56] **References Cited**

U.S. PATENT DOCUMENTS

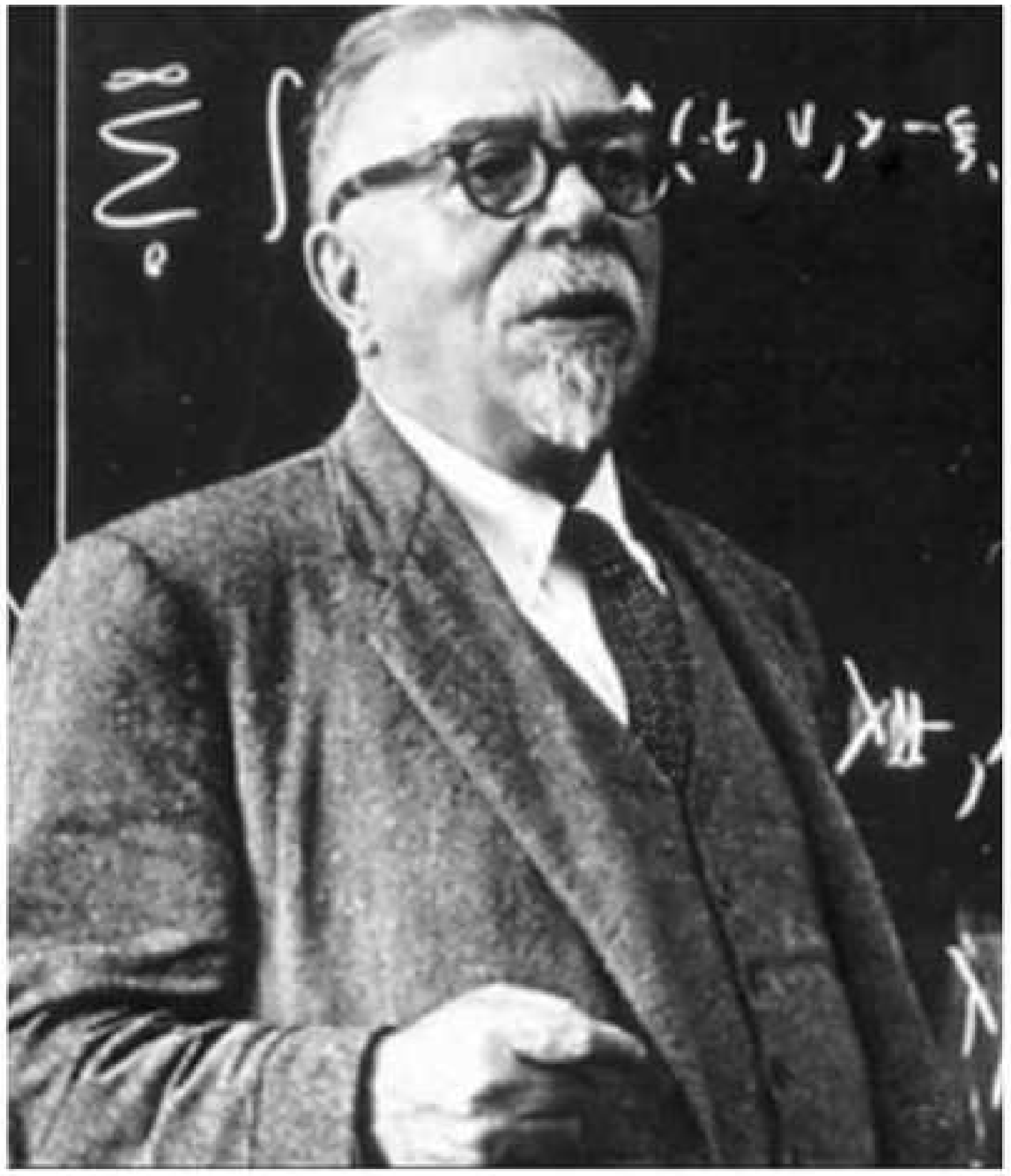
2,708,617	5/1955	Magat et al.	264/183 X
2,908,545	10/1959	Teja	264/22 X
3,306,835	2/1967	Magnus	425/174.4 X
3,635,625	1/1972	Voss	425/162 X
3,775,036	11/1973	Winning	425/174.4
3,974,248	8/1976	Atkinson	425/162 X
4,041,476	8/1977	Swainson	365/119
4,078,229	3/1978	Swainson et al.	365/107
4,081,276	3/1978	Crivello	430/269
4,238,840	12/1980	Swainson	365/119
4,252,514	2/1981	Gates	425/162
4,288,861	9/1981	Swainson et al.	365/127
4,292,015	9/1981	Hritz	425/162 X
4,329,135	5/1982	Beck	425/174
4,333,165	6/1982	Swainson et al.	365/127 X
4,374,077	2/1983	Kerfeld	264/22
4,466,080	8/1984	Swainson et al.	365/127 X
4,471,470	9/1984	Swainson et al.	365/127

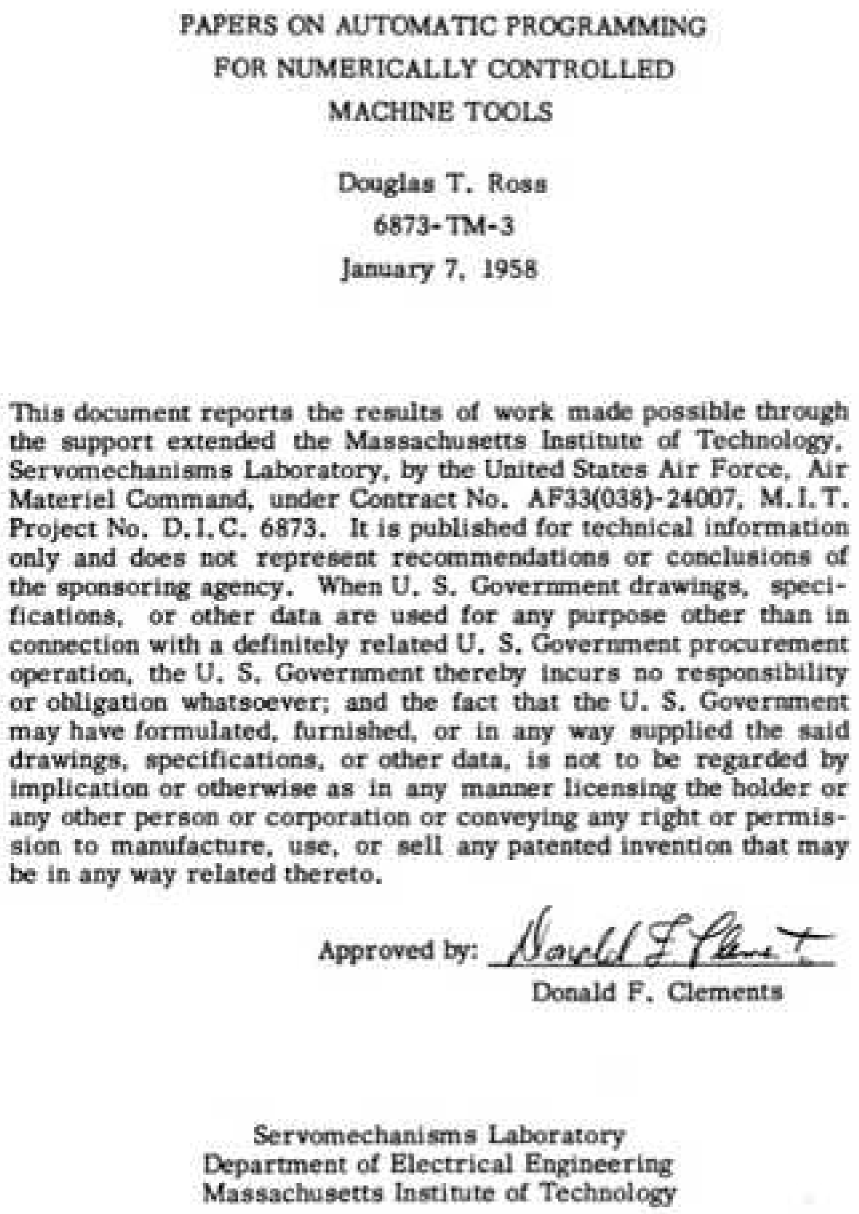
Primary Examiner—J. Howard Flint, Jr.
Attorney, Agent, or Firm—Fulwider, Patton, Rieber, Lee & Utecht

[57] **ABSTRACT**

A system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed at a selected surface of a fluid medium capable of altering its physical state in response to appropriate synergistic stimulation by impinging radiation, particle bombardment or chemical reaction, successive adjacent laminae, representing corresponding successive adjacent cross-sections of the object, being automatically formed and integrated together to provide a step-wise laminar buildup of the desired object, whereby a three-dimensional object is formed and drawn from a substantially planar surface of the fluid medium during the forming process.

47 Claims, 8 Drawing Figures





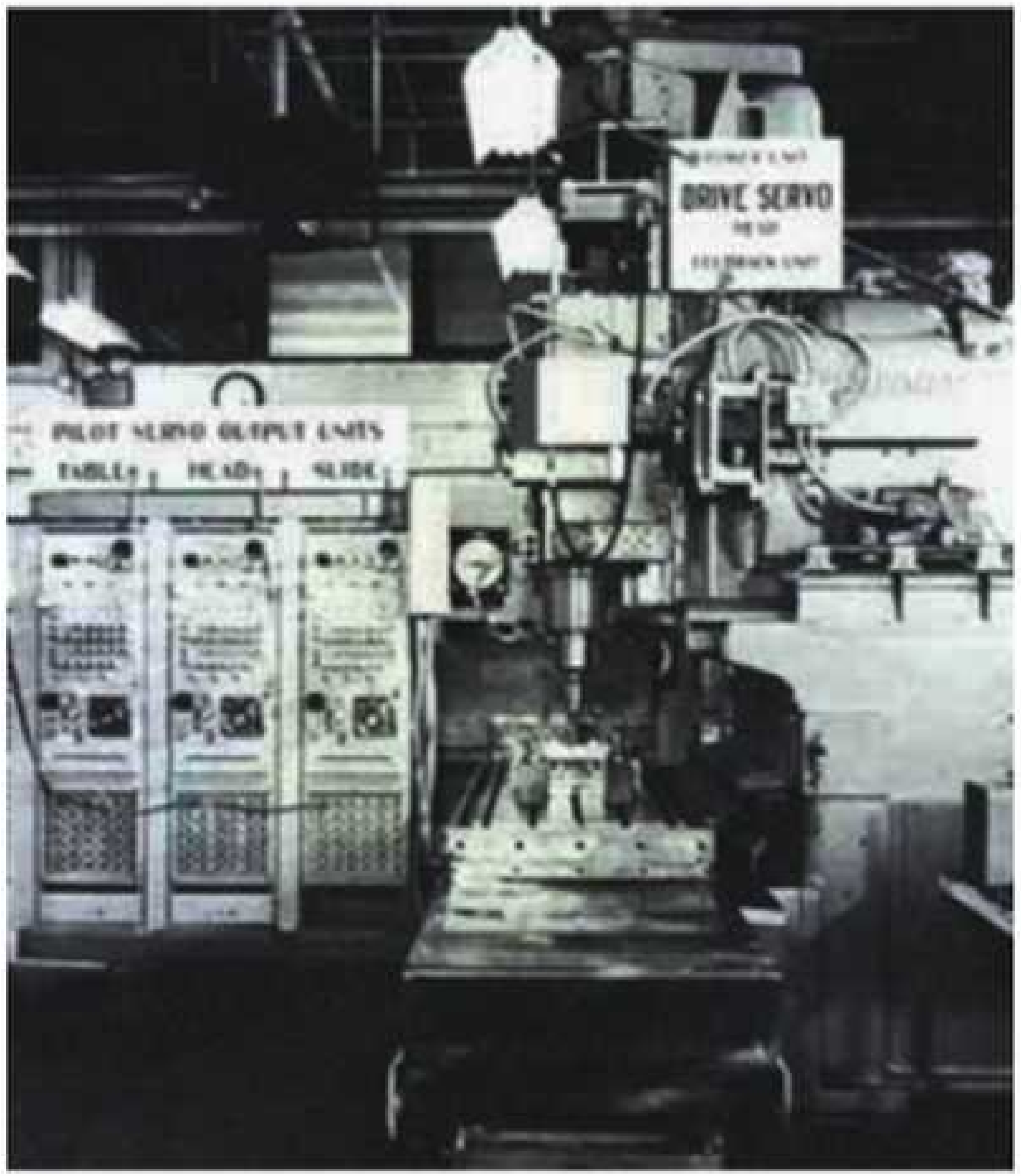
PAPERS ON AUTOMATIC PROGRAMMING
FOR NUMERICALLY CONTROLLED
MACHINE TOOLS

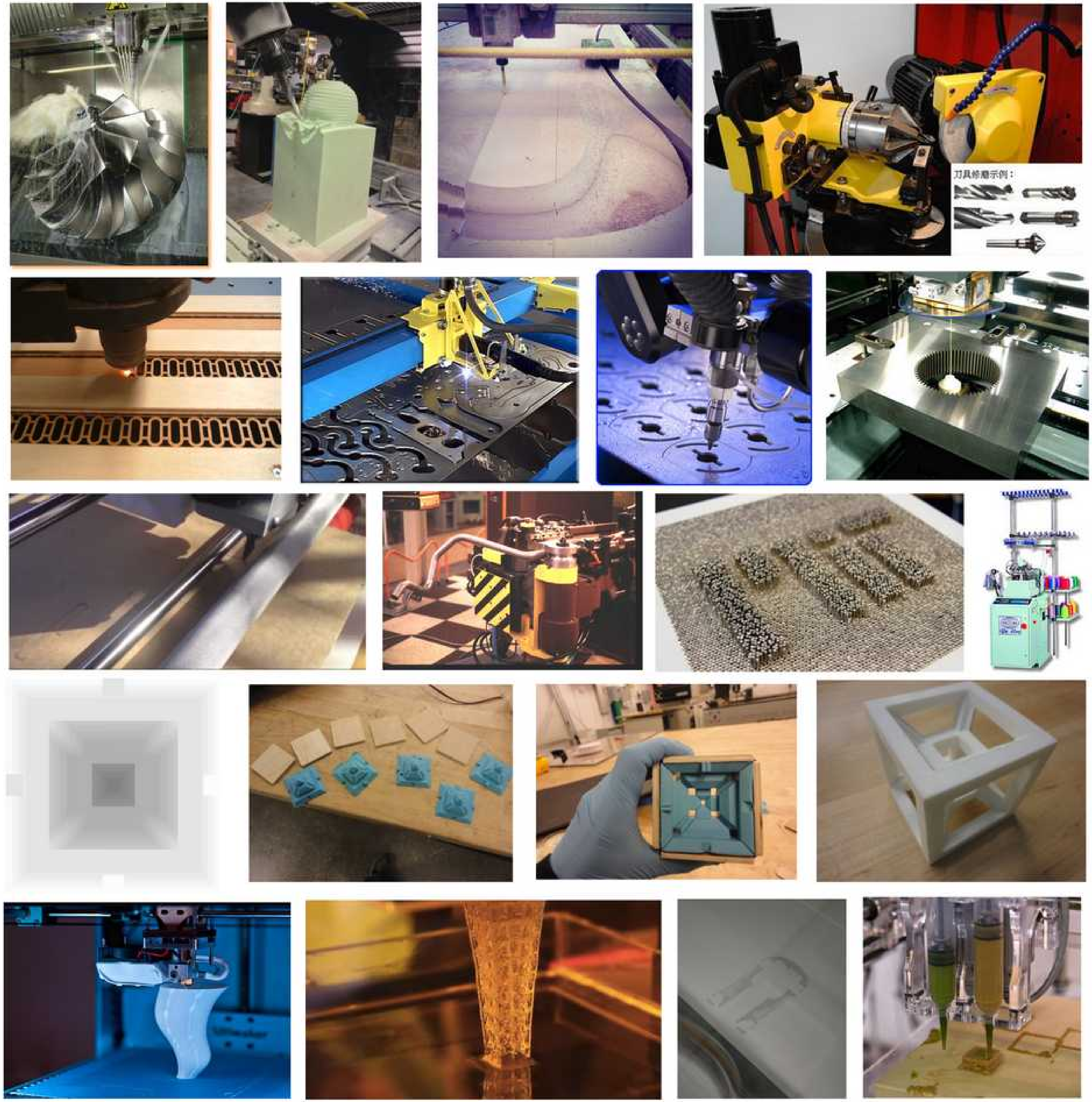
Douglas T. Ross
6873-TM-3
January 7, 1958

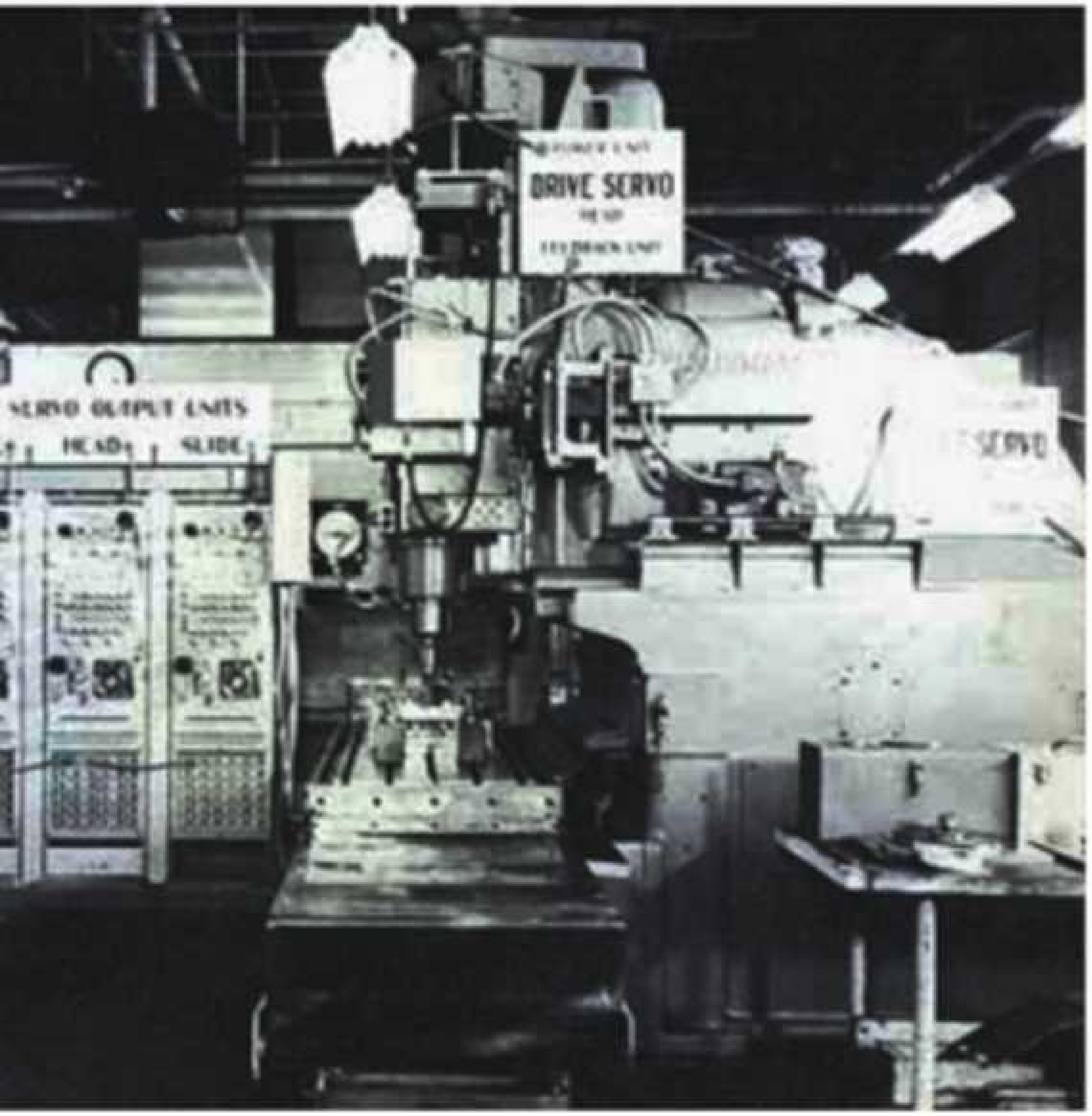
This document reports the results of work made possible through the support extended the Massachusetts Institute of Technology, Servomechanisms Laboratory, by the United States Air Force, Air Materiel Command, under Contract No. AF33(038)-24007, M.I.T. Project No. D.I.C. 6873. It is published for technical information only and does not represent recommendations or conclusions of the sponsoring agency. When U. S. Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related U. S. Government procurement operation, the U. S. Government thereby incurs no responsibility or obligation whatsoever; and the fact that the U. S. Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation or conveying any right or permission to manufacture, use, or sell any patented invention that may be in any way related thereto.

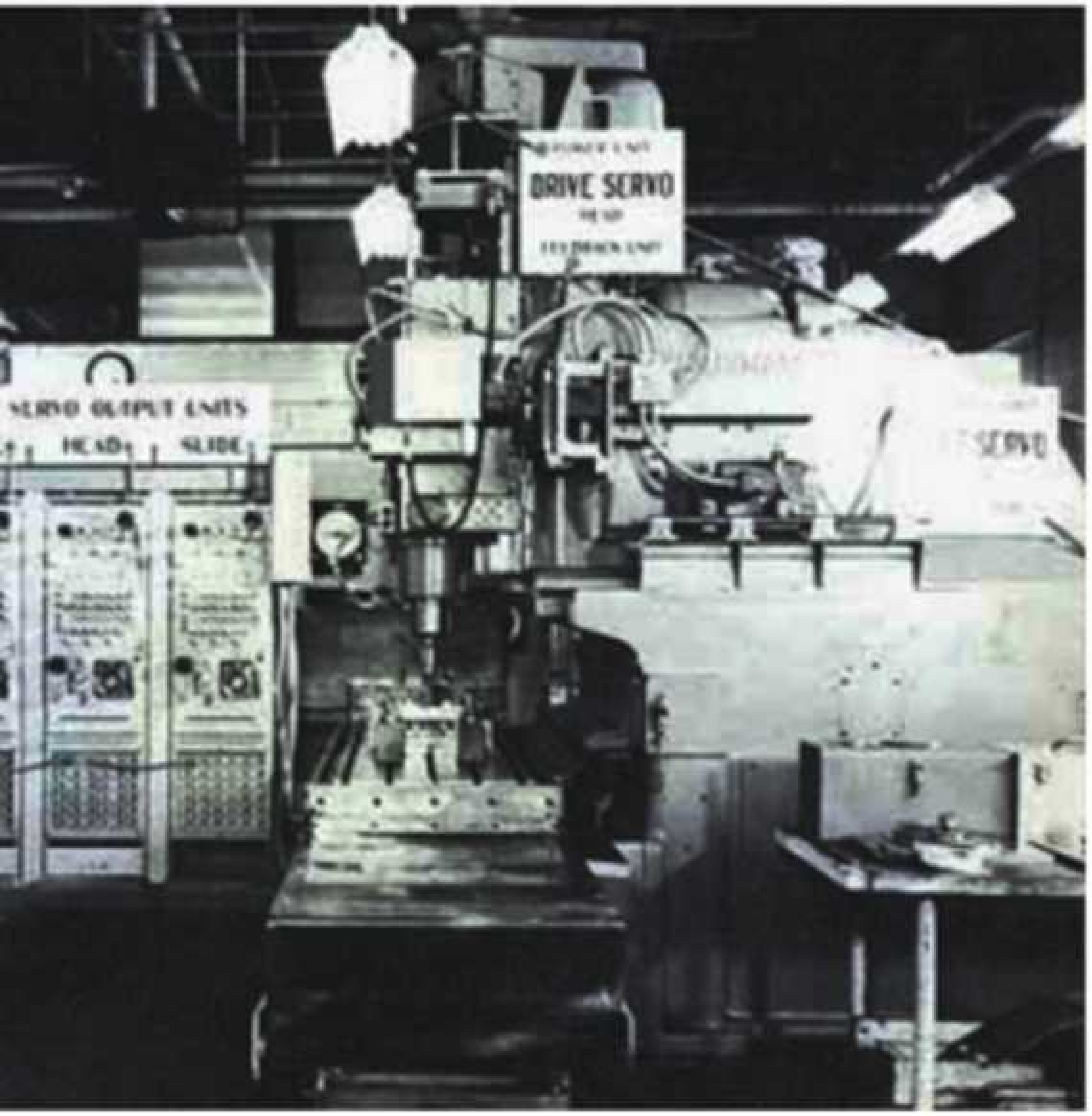
Approved by: ______
Donald F. Clements

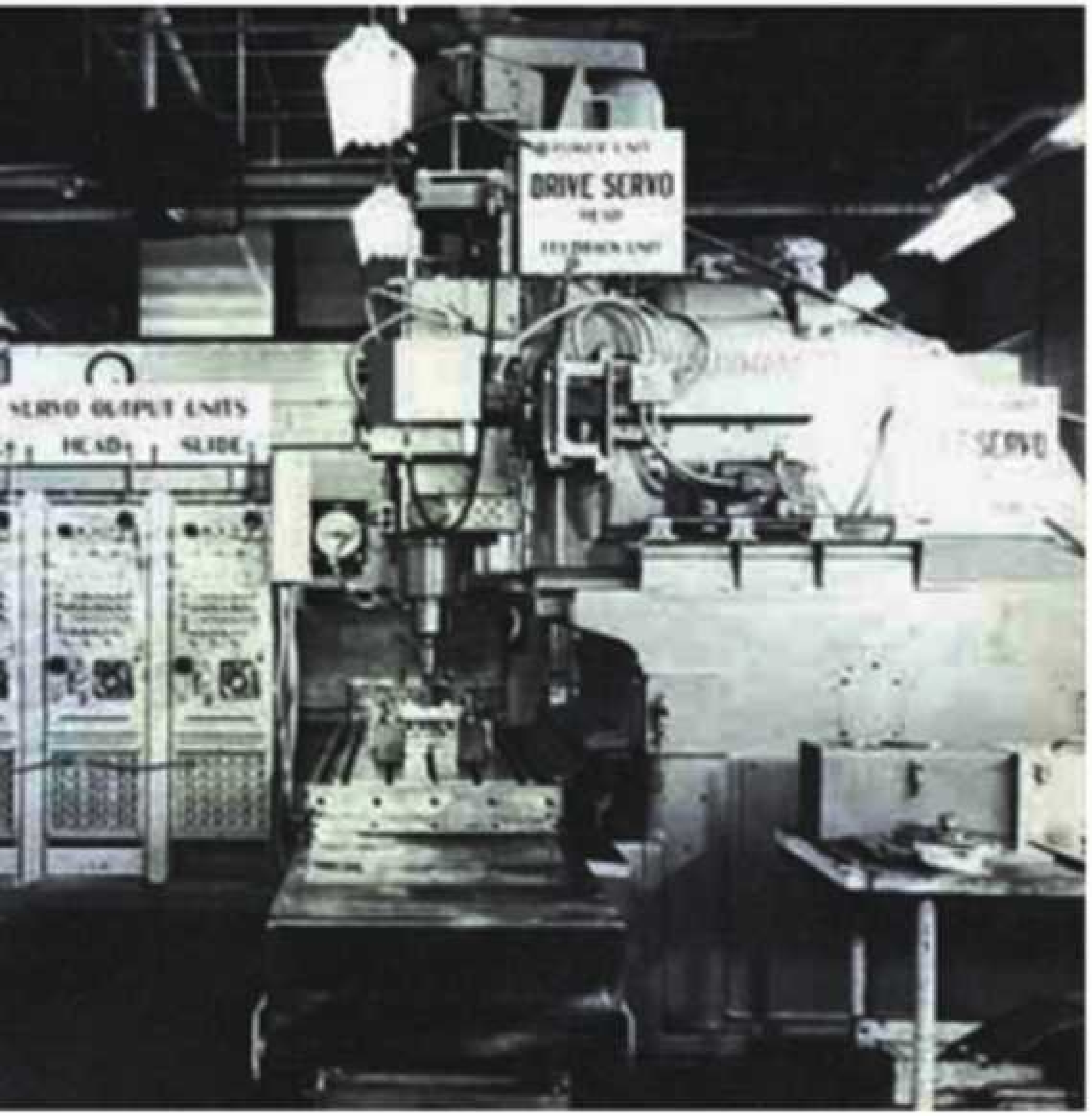
Servomechanisms Laboratory
Department of Electrical Engineering
Massachusetts Institute of Technology



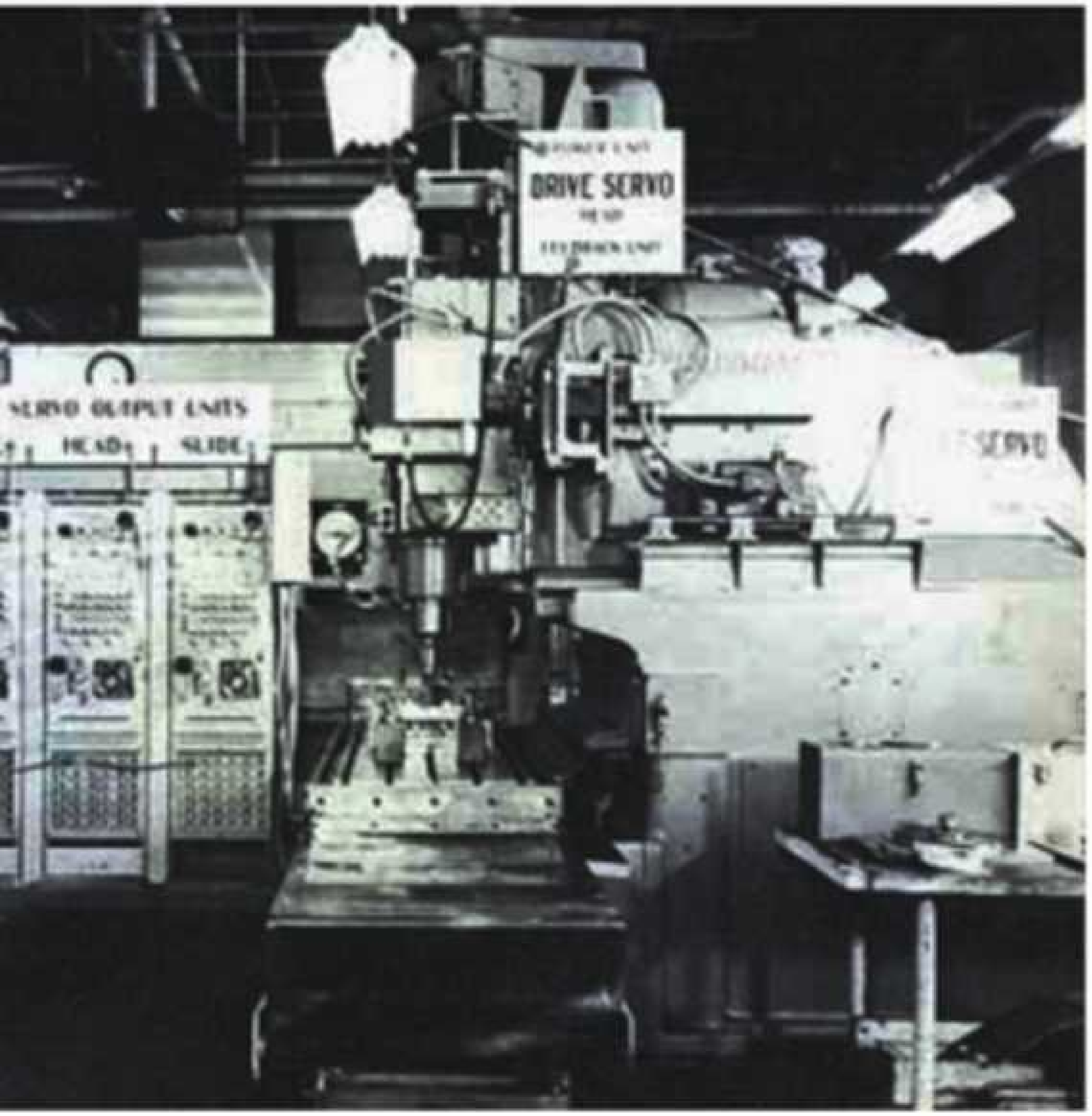

刀具修磨示例：


POWER UNIT
DRIVE SERVO
HEAD
FEEDBACK UNIT
SERVO OUTPUT UNITS
HEAD
SLIDE
SERVO

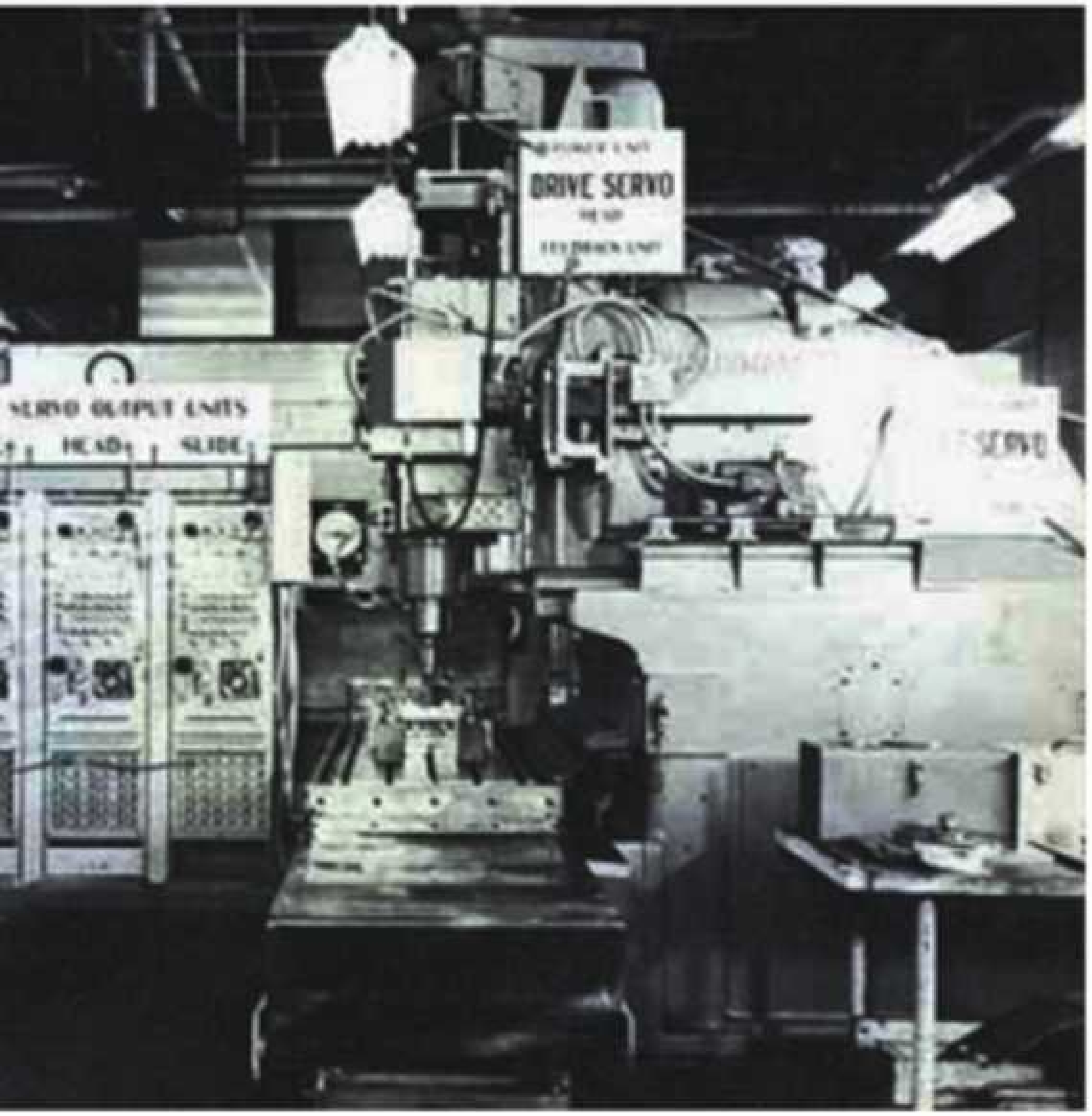

POWER UNIT
DRIVE SERVO
HEAD
FEEDBACK UNIT
SERVO OUTPUT UNITS
HEAD
SLIDE
SERVO



- **metrology**
- **error correction**
- **functional**
- **reusable**



- **discrete set of parts**
- **discrete relative positions and orientations**



- **discrete set of parts**
- **discrete relative positions and orientations**

= digital material

Digital materials for digital printing

George A. Popescu (MIT, Center for Bits and Atoms), Tushar Mahale (North Carolina State University), Neil Gershenfeld (MIT Center for Bits and Atoms).

Abstract

Conventional three-dimensional printing processes are material-dependent, and are irreversible. We present an alternative approach based on three-dimensional assembly of mass-produced two-dimensional components of digital material. This significantly enlarges the available material set, allows reversible disassembly, and imposes constraints that reduce the accumulation of local positioning errors in constructing a global shape. Experimental work on material properties and dimensional scaling of the digital material will be presented, with application in assembling functional structures. We propose that assembling digital material will be the future of 3-dimensional free-form fabrication of functional materials.

Most existing commercial free-form fabrication printers build by putting together small quantities of no more than a few expensive materials. In order to make high-resolution objects they need to be very precise and therefore cost between tens and hundreds of thousands of dollars and are operated by skilled technicians. On the other hand young children build 3-dimensional structures out of LEGO with their hands. LEGO structures are cheap, quick and easy to make, reversible and most importantly they are more precise than the kids who build them. However, they are big and are only made out of ABS plastic. We believe that digital materials bring reversibility, simplicity, low cost and speed to free form fabrication in addition to a larger material set.

Previous research on structures built out of many discrete parts involved self assembly [1], error correction self assembly [2], programmable self-assembly [3] and folding[4]. We rely on a digital printer, as presented in [5] which will assemble the structure by picking and placing the bricks forming the digital material.

We define a digital material as a discrete set of components that can be of any sizes and shape, made out of various materials and that can fit together in various ways (press fit, friction fit, snap fit, reflow binding, etc.). However the components of a digital material must satisfy the following properties which are familiar to many toy assembly kits:

1. All components can be decomposed into smaller elementary geometrical shapes.
2. Two components can form a finite number of links.
3. The links between two components are reversible.

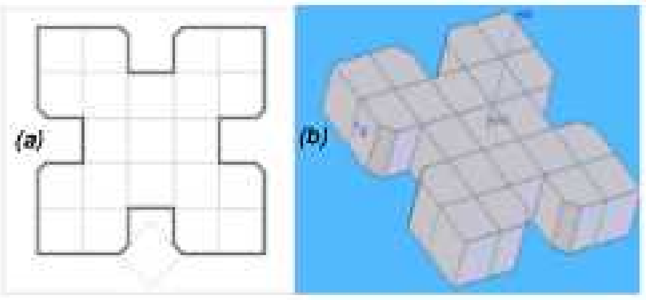


Figure 1 ***A drawing (a) and a 3D model (b) of a square GIK part. A square GIK is made out of 21 cubes among which 8 have chamfers. Many other geometries (triangle, rectangles, …) are possible.***

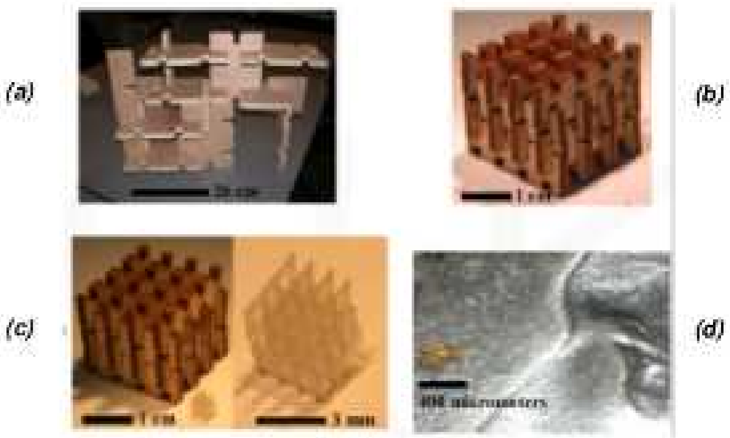


Figure 2 ***GIK structures of different sizes & shapes: (a) meter (in plywood) , (b) centimeter (plywood), (c) millimeter (celluloid) , (d) μm (Kepton). You can see the mm and cm scale structures side by side in (c). The μm structure is on top of a dime for scale purposes.***

Figure 3 ***GIK parts made out of different material: plywood, Plexiglas, aluminum and fiberglass composite material, stainless steel, transparency (celluloid) and cardboard.***

GIK[*] as described in figure 1 is as an example of digital material. GIK bricks (see Fig. 1, 2, 3) can be cut in 2-dimensions which makes them very easy to make at any scale (Fig. 2). They can be press fit together to form space filling voxels that can be connected and disconnected at will making the construction reversible. In addition, as seen in Fig. 3 they can be made out of a variety of materials. Below eye resolution GIK parts (1μm and smaller) will have macro-scale behavior but will form high resolution objects which will seem continuous. GIK building blocks can be compared to an atom that assembles to form a

---

[*] GIK, initially Grace's Invention Kit after its inventor Grace Gershenfeld, became the Great Invention Kit after Eli Gershenfeld contributed, than simply GIK.

DF 2006 International Conference on Digital Fabrication Technologies, Denver, Colorado (2006)

Digital Printing of Digital Materials

George A. Popescu (MIT Center for Bits and Atoms), Patrik Kunzler(MIT Center for Bits and Atoms), Neil Gershenfeld (MIT Center for Bits and Atoms).

We present a printer that builds functional three-dimensional structures by reversible assembly of a discrete set of components, "digital materials". This approach uses the components rather than a control system to impose the spatial and functional constraints. Printing can be performed as a parallel rather than a linear process. The printing process is reversible for re-use of the pieces or for error correction at any point in the object's life. Error detection, error-reduction and error-tolerance during assembly allows for reliable, high throughput printing. We are presenting development approaches to such a printing device.

The paper "Digital material for digital printing" [1] presents a digital material that can be used to 3-D print functional free-form structures. In the present paper we are describing the technical architecture of a possible printer that can do the assembly. While this assembler will be designed to use vertical GIK, a version of digital material similar to GIK [1], one should be able to modify it to assemble any digital material. Vertical GIK , as presented in figure 1, has the same properties as GIK, is forming the same press fit links as GIK, but can only be assembled vertically. Therefore a vertical GIK structure is formed (as shown in figure 1) by rotating each layer in respect to the last one by 90 degrees in order to brace two lines together.

Because the present machine will assemble a digital material which is error-tolerant and error-reducing, its metrology will be very simple. As shown in figures 1 and 2, in order to assemble a GIK structure the assembler only has to press the parts together vertically. It is therefore a 2.5 axes assembler. It's x and y precision has to be at worse the chamfer dimension ε (as presented in [1]). The chamfer size ε being typically about 1/20 of the size of a vertical GIK brick the printer needs a x-y precision of about 1 micrometer in order to assemble 20 micrometer big vertical GIK.

As shown in figure 2, the assembler will use Blank parts to create overhangs or as place holders. The Blank parts are unable to create links with GIK parts but are the same dimension as a GIK part. Once the structure will be built one can discard the Blanks parts by shaking the resulting structure.

If a GIK part is 20 micrometer big, in order to build a 10 cubic cm structure one would need about 100 billion parts. In order to build such a structure in a reasonable amount of time (1 day) the assembler has to add about 1 million parts a second. This can only be done if the assembler is adding the 1 million parts simultaneously (in parallel).

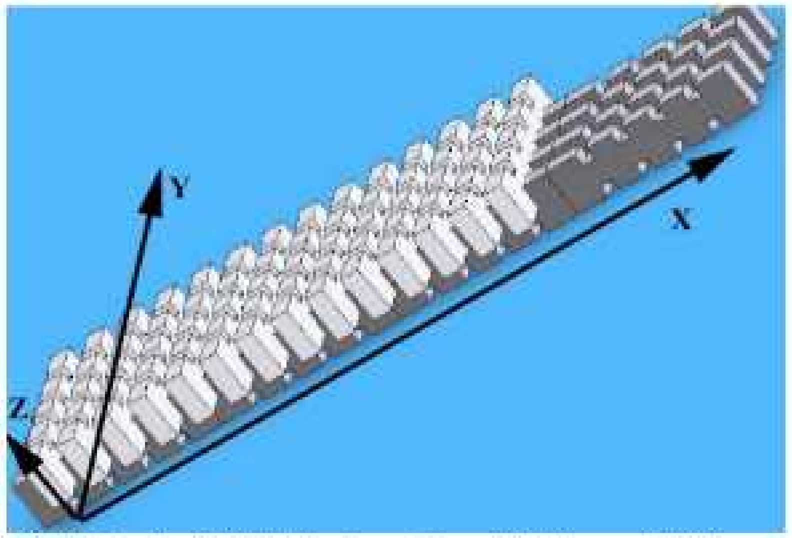


Figure 1 ***vertical GIK bricks forming an incomplete 2 layer vertical GIK structure. One can notice the 90 degree rotation between layers for bracing***

Assembling Strategy

A GIK structure is composed of layers of GIK. Each GIK layer is composed of GIK lines. The main idea guiding the assembler's architecture is that the assembler is always adding lines of constant length, one entire line at a time. However each line is composed of GIK only in the positions where it is supposed to add a GIK to the structure and of Blank parts otherwise. This way the structure to be built is

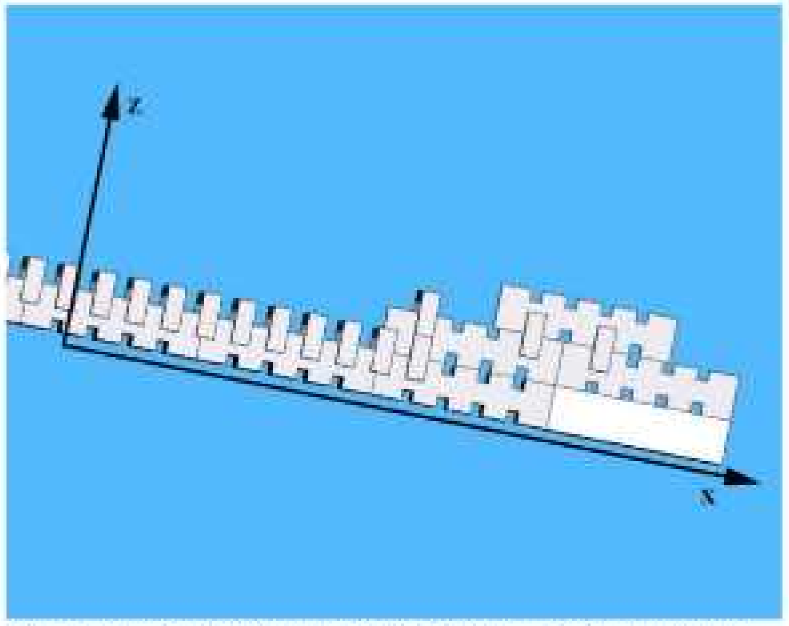


Figure 2 ***vertical GIK (gray) and Blank (white) parts forming an overhang structure. One can notice that Blank and vertical GIK are the same size and that Blank and vertical GIK don't form any links.***

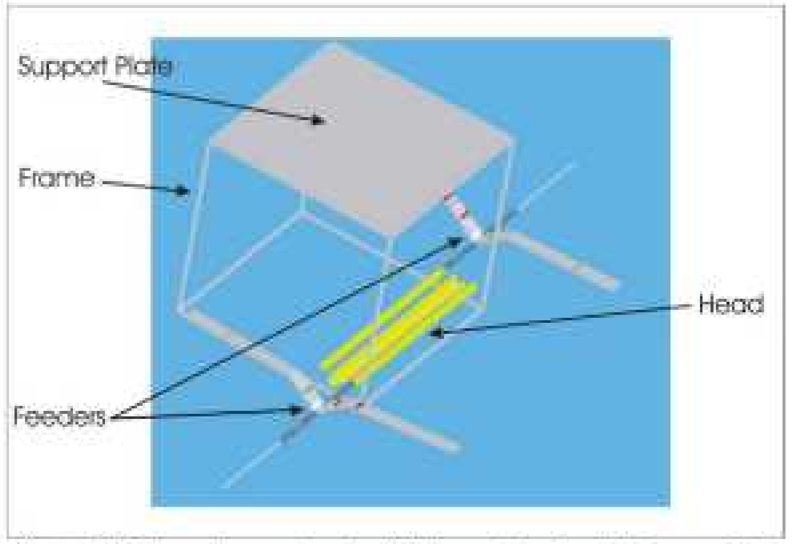
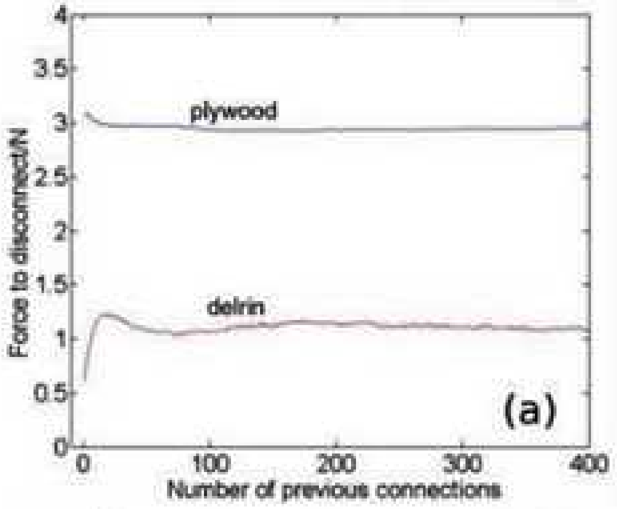
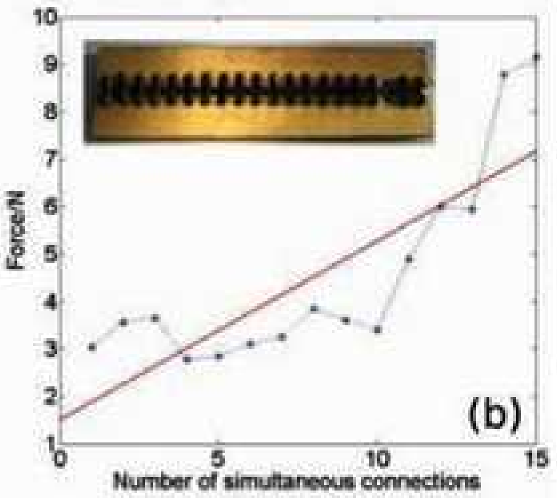


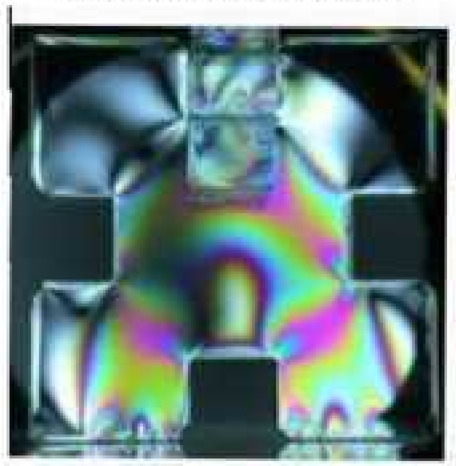
Figure 3 ***Schematic overview of a digital assembler. The digital assembler consists of a support plate which provides support for the first layer of vertical GIK and holds the object to be assembled, one or more assembly heads (yellow), and 2 feeders for each head, all of which are held together on a frame.***

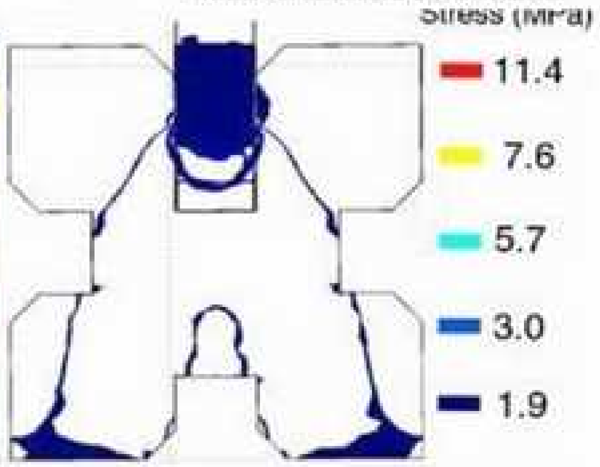
DF 2006 International Conference on Digital Fabrication Technologies, Denver, Colorado (2006)

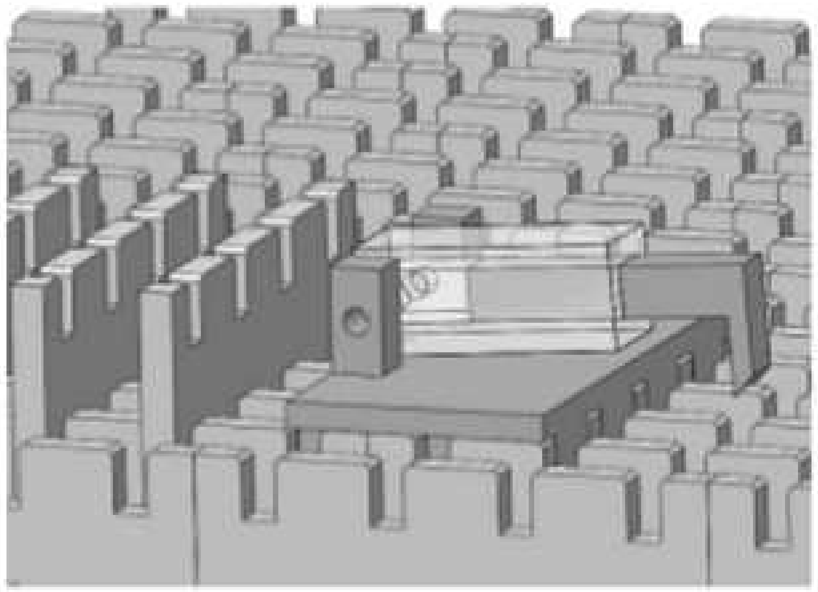
digital materials

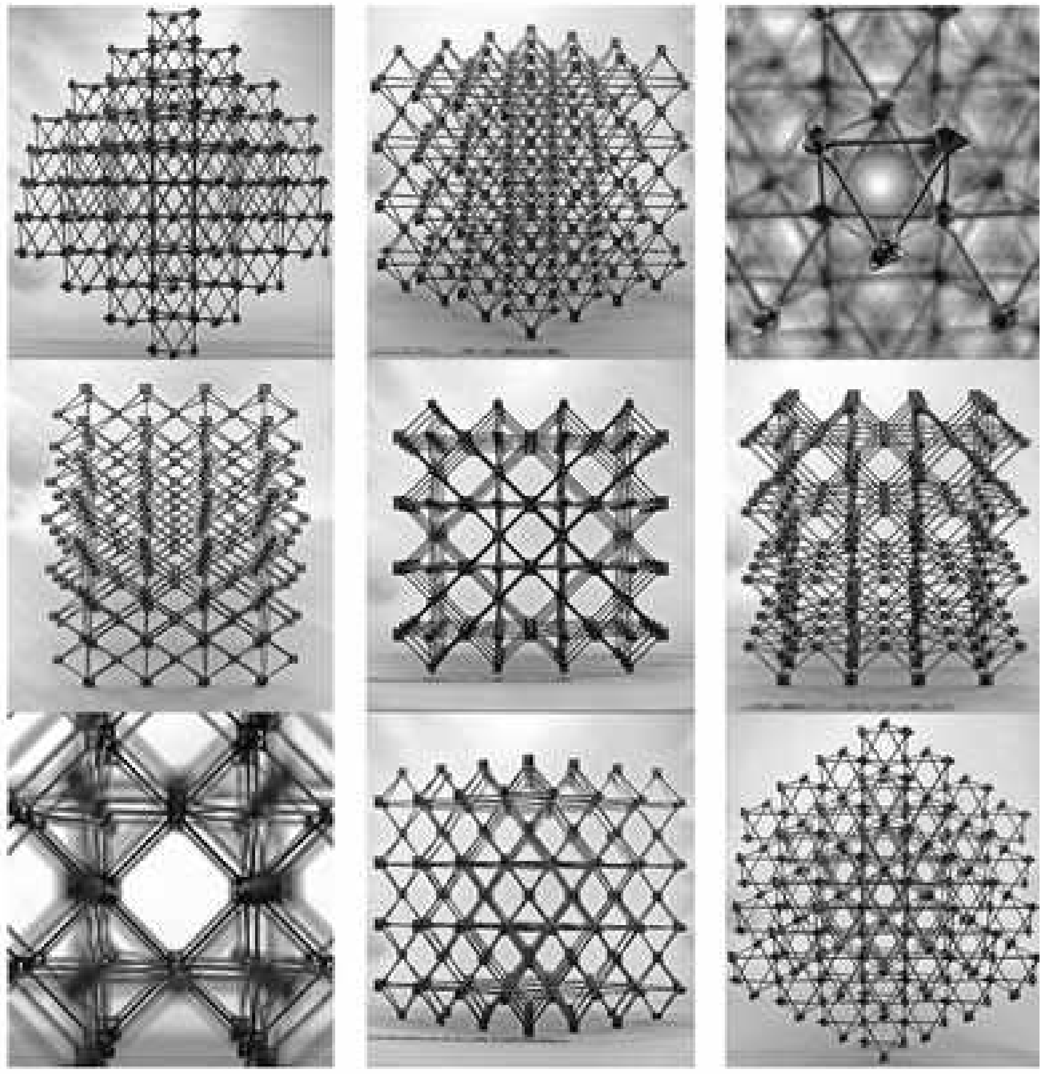


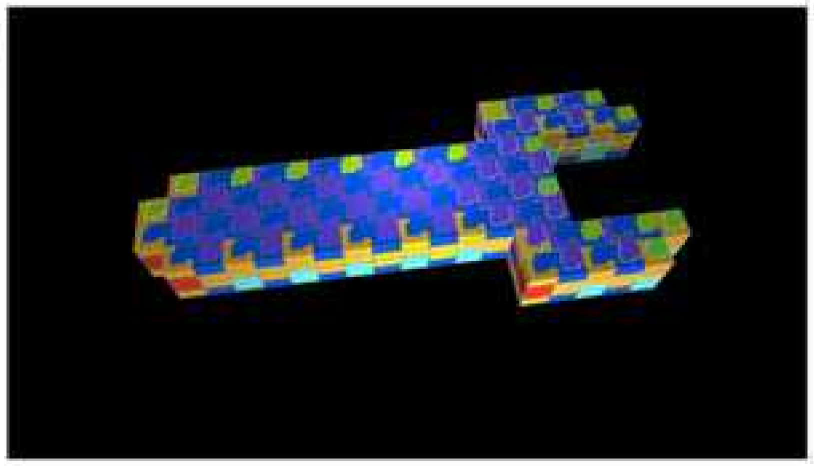


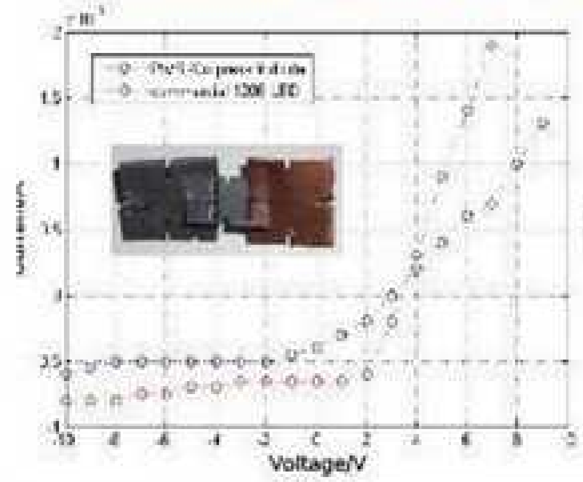


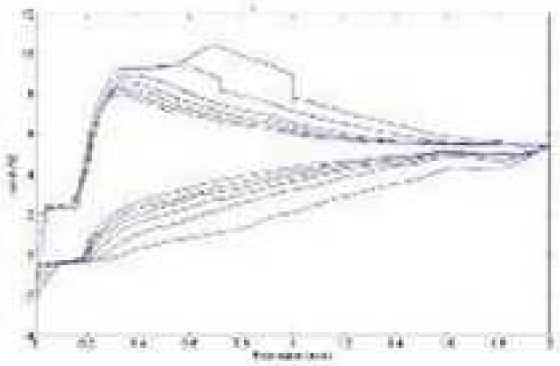


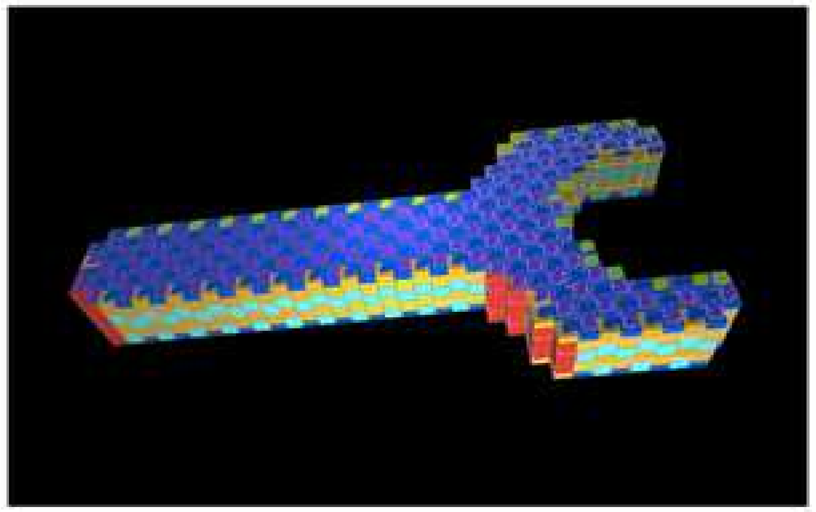


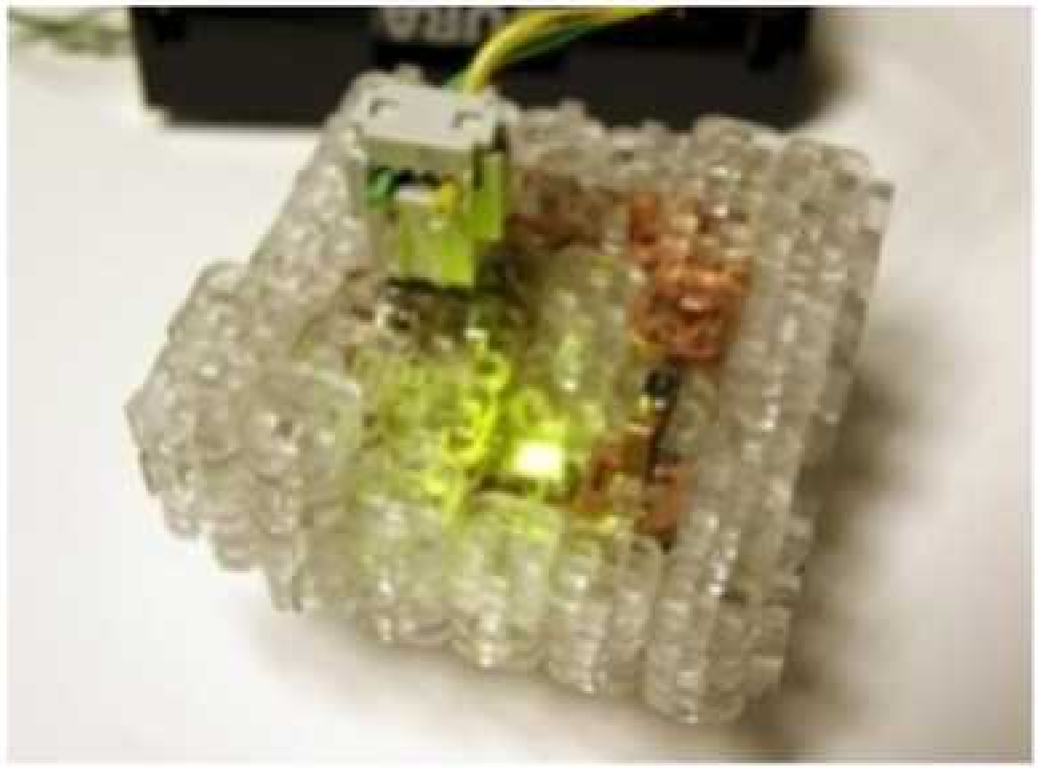


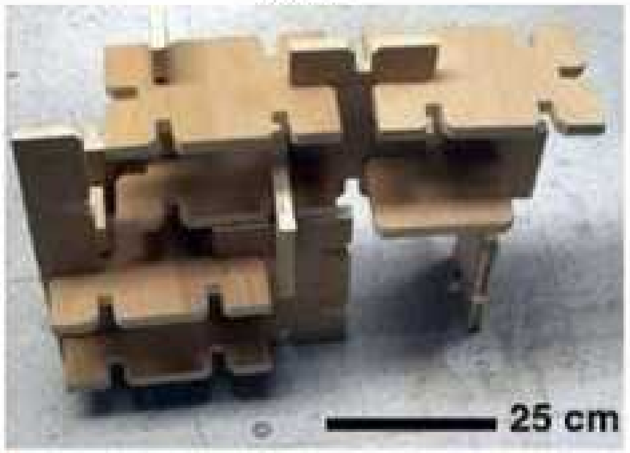


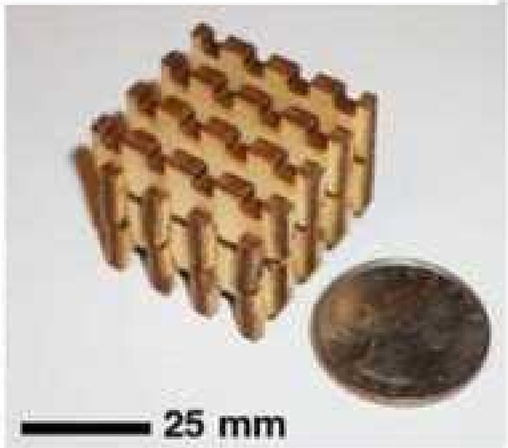


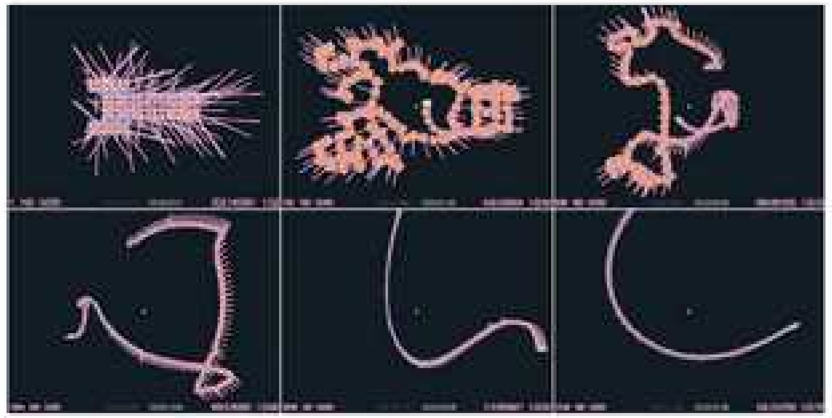


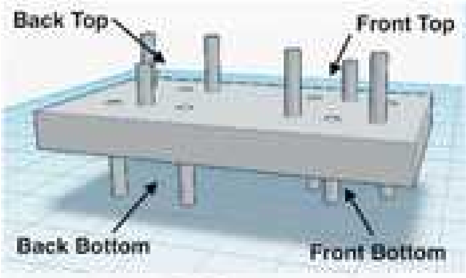


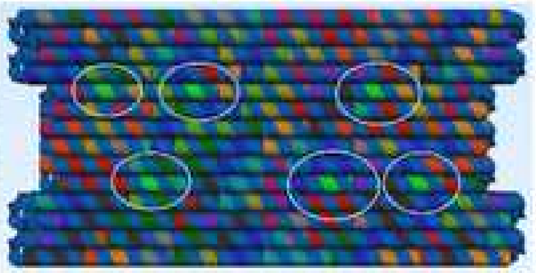


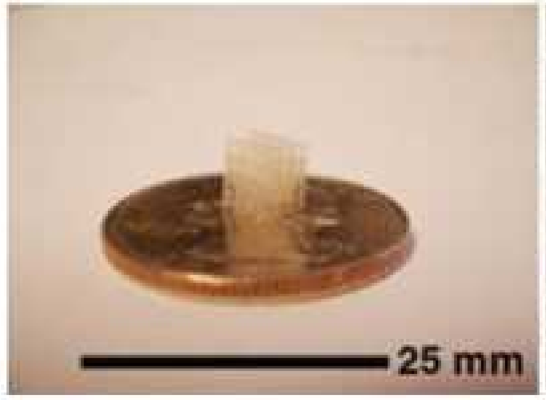


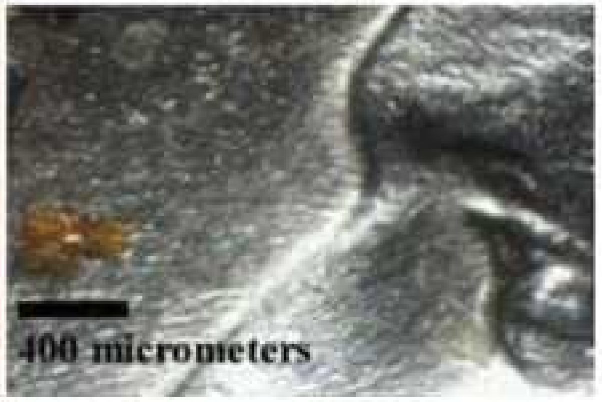


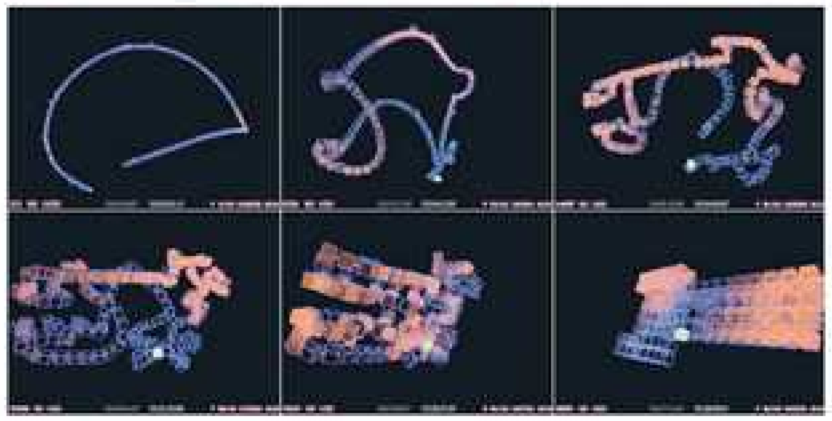


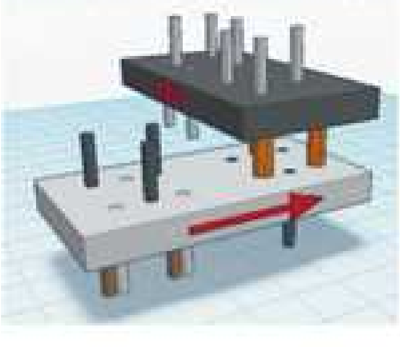


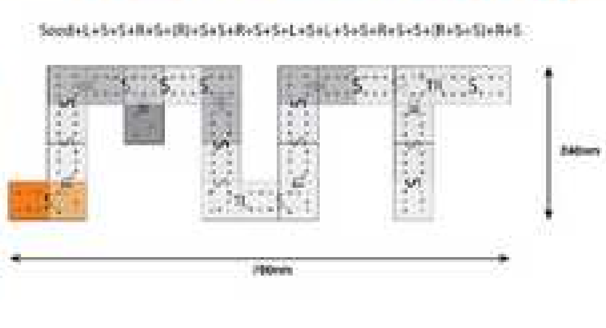












ON THE DECREASE OF ENTROPY IN A THERMODYNAMIC SYSTEM BY THE INTERVENTION OF INTELLIGENT BEINGS

LEO SZILARD

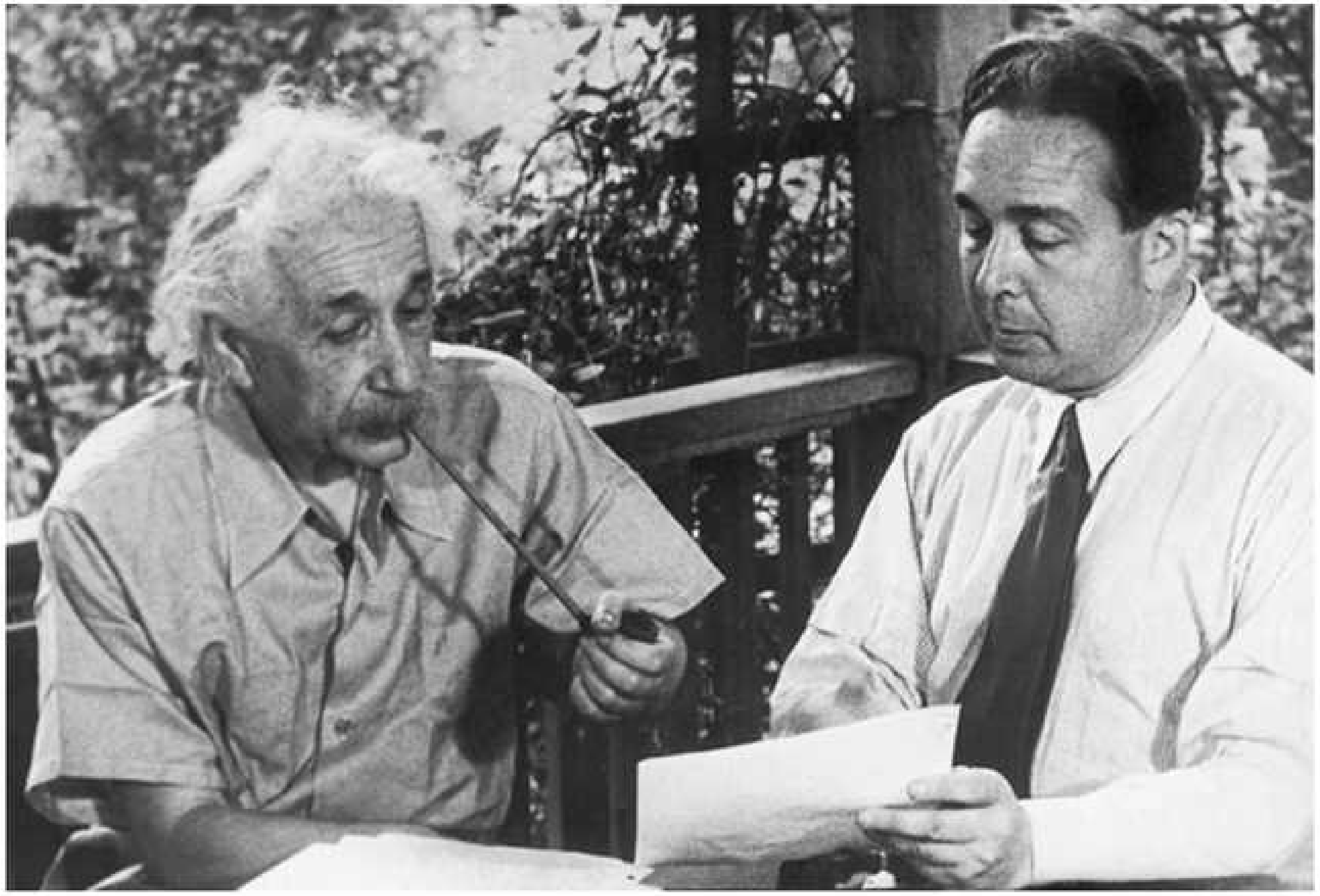
Translated by Anatol Rapoport and Mechthilde Knoller from the original article "Über die Entropieverminderung in einem thermodynamischen System bei Eingriffen intelligenter Wesen." Zeitschrift für Physik, 1929, 53, 840–856.

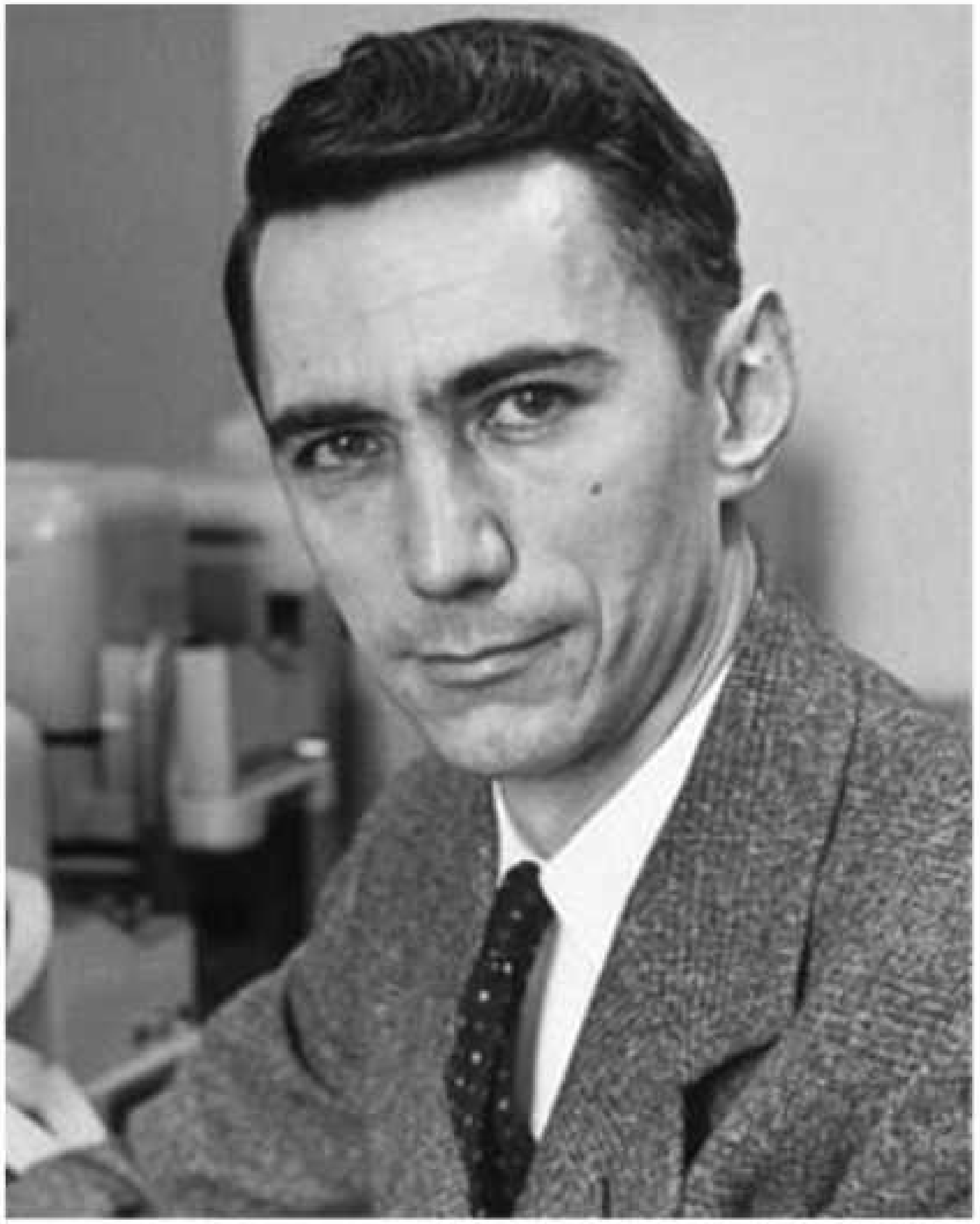
* * *

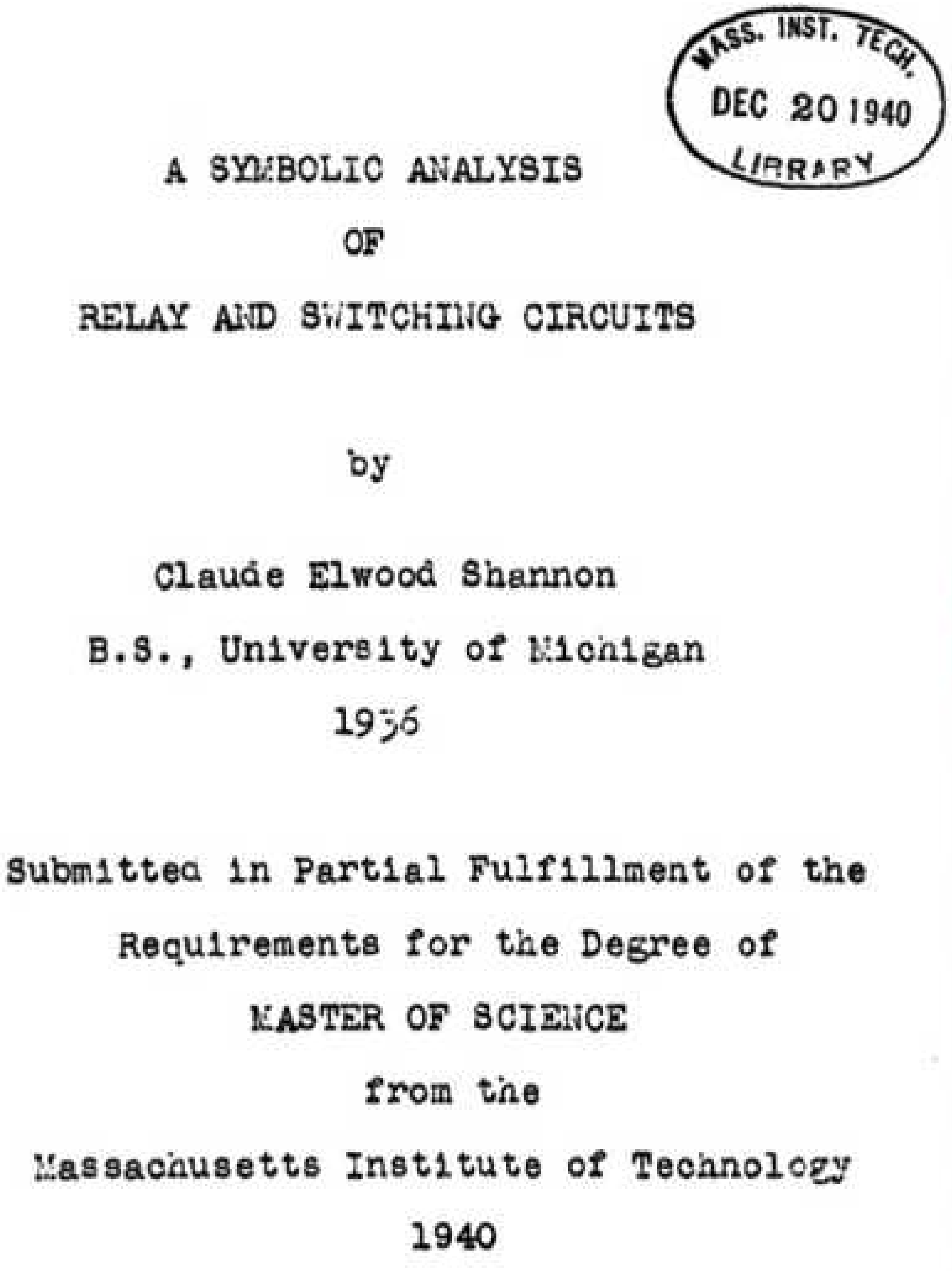
The objective of the investigation is to find the conditions which apparently allow the construction of a perpetual-motion machine of the second kind, if one permits an intelligent being to intervene in a thermodynamic system. When such beings make measurements, they make the system behave in a manner distinctly different from the way a mechanical system behaves when left to itself. We show that it is a sort of a memory faculty, manifested by a system where measurements occur, that might cause a permanent decrease of entropy and thus a violation of the Second Law of Thermodynamics, were it not for the fact that the measurements themselves are necessarily accompanied by a production of entropy. At first we calculate this production of entropy quite generally from the postulate that full compensation is made in the sense of the Second Law (Equation [1]). Second, by using an inanimate device able to make measurements—however under continual entropy production—we shall calculate the resulting quantity of entropy. We find that it is exactly as great as is necessary for full compensation. The actual production of entropy in connection with the measurement, therefore, need not be greater than Equation (1) requires.

* * *

THERE is an objection, already historical, against the universal validity of the Second Law of Thermodynamics, which indeed looks rather ominous. The objection is embodied in the notion of Maxwell's demon, who in a different form appears even nowadays again and again; perhaps not unreasonably, inasmuch as behind the precisely formulated question quantitative connections seem to be hidden which to date have not been clarified. The objection in its original formulation concerns a demon who catches the fast molecules and lets the slow





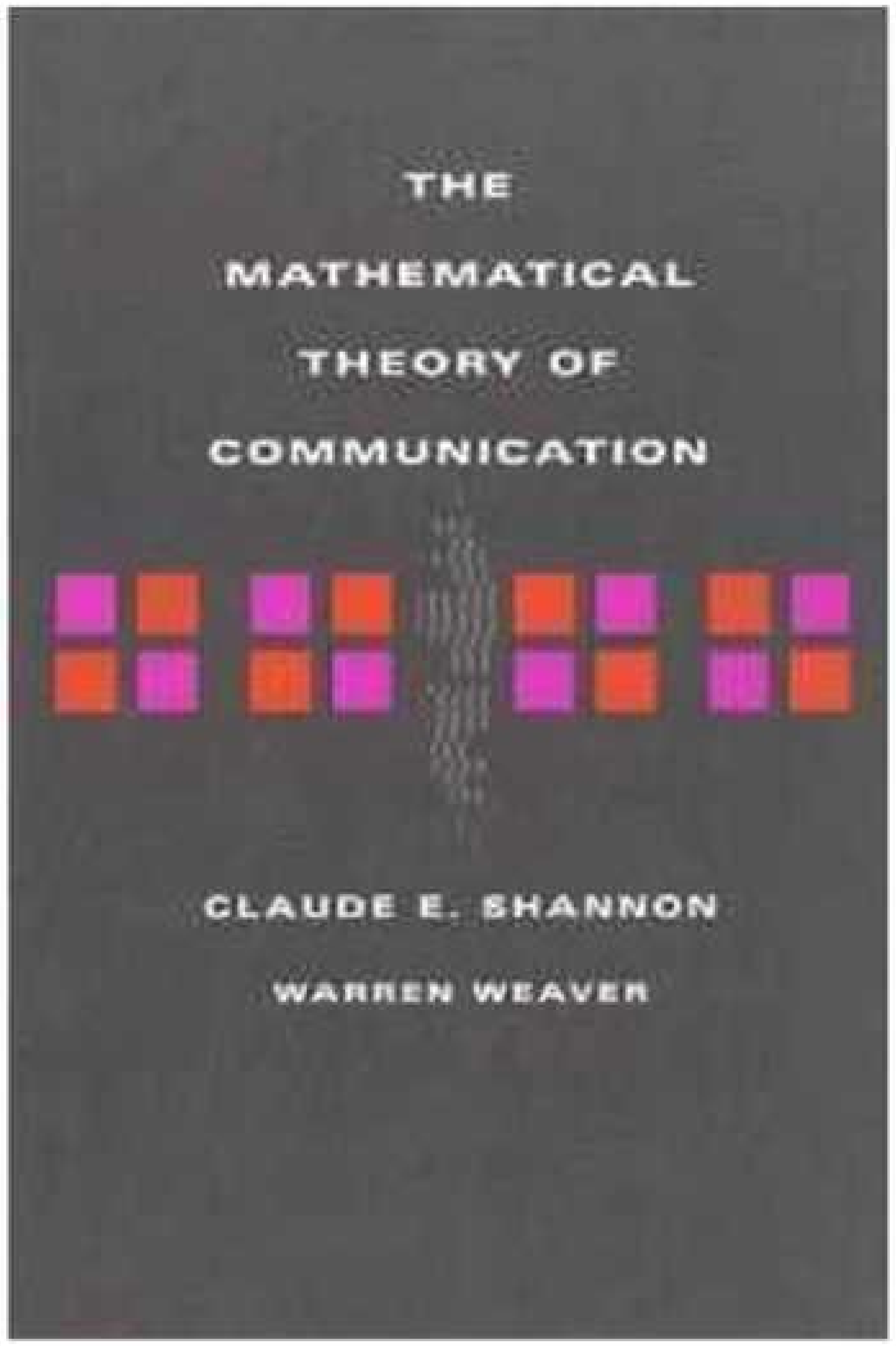


A SYMBOLIC ANALYSIS
OF
RELAY AND SWITCHING CIRCUITS

by

Claude Elwood Shannon
B.S., University of Michigan
1936

Submitted in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
from the
Massachusetts Institute of Technology
1940



THE
MATHEMATICAL
THEORY OF
COMMUNICATION

CLAUDE E. SHANNON
WARREN WEAVER

Lectures on

PROBABILISTIC LOGICS AND THE SYNTHESIS OF RELIABLE ORGANISMS FROM UNRELIABLE COMPONENTS

delivered by

PROFESSOR J. von NEUMANN

The Institute for Advanced Study
Princeton, N. J.

at the

CALIFORNIA INSTITUTE OF TECHNOLOGY

January 4-15, 1952

Notes by

R. S. PIERCE

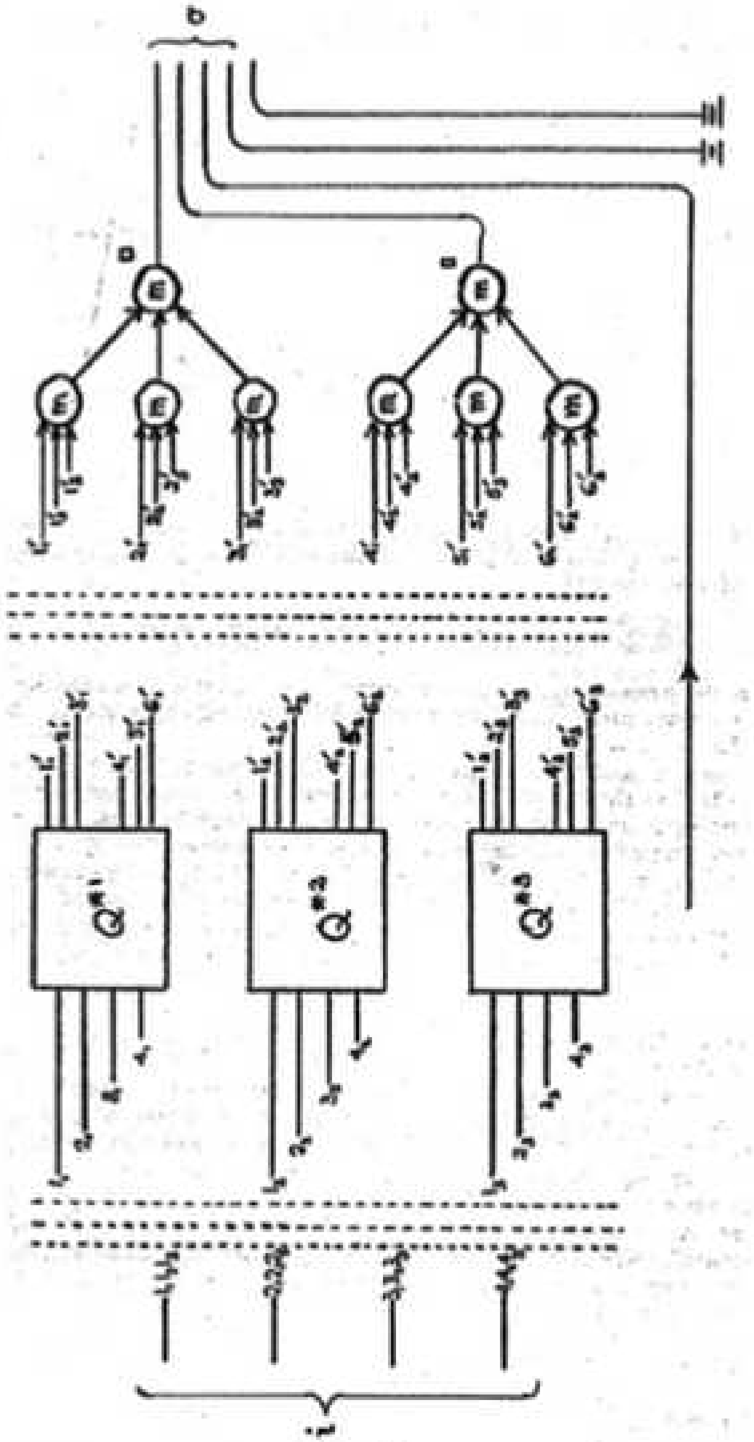
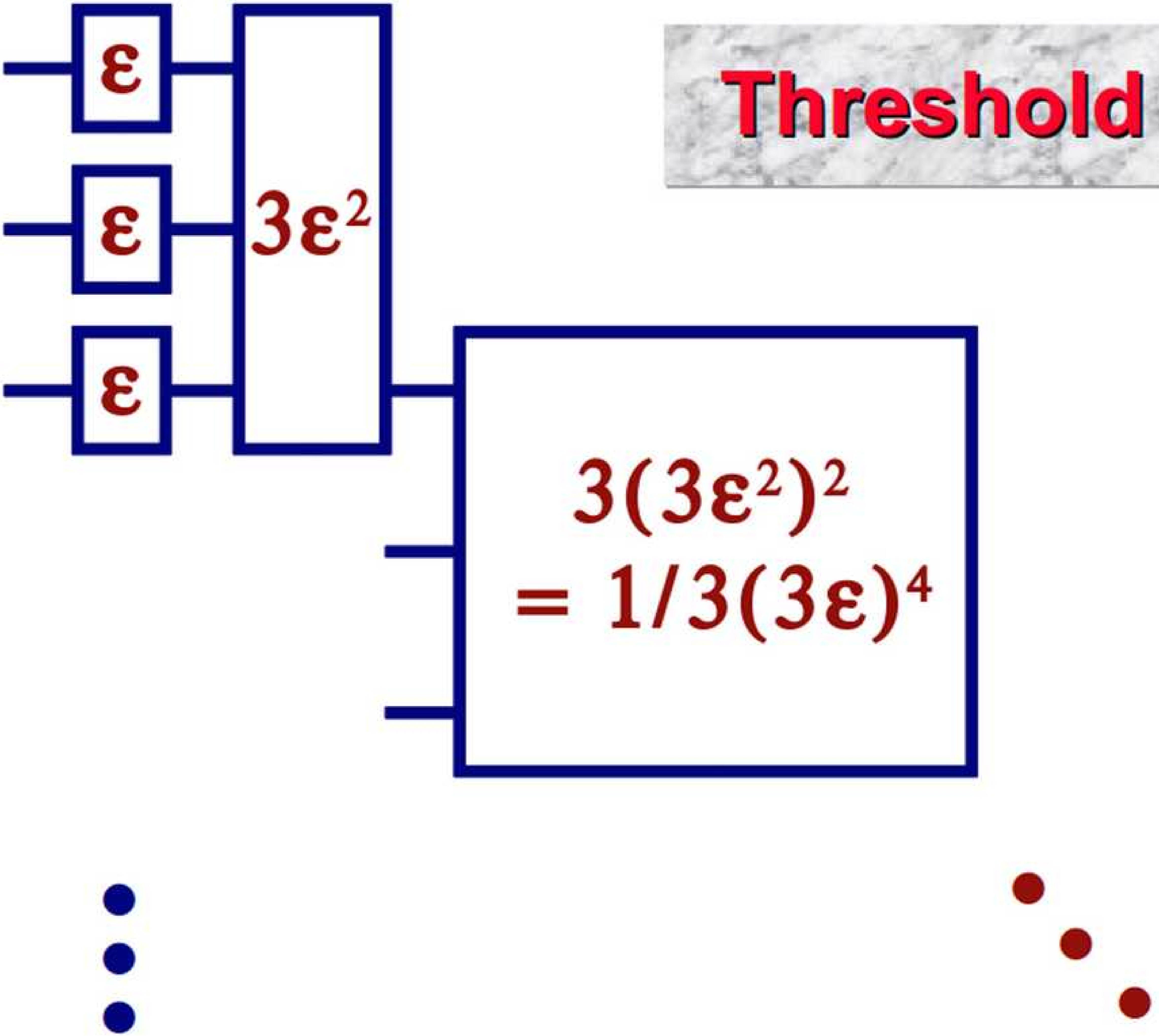


Fig. 29

Threshold Theorems



ε

ε

ε

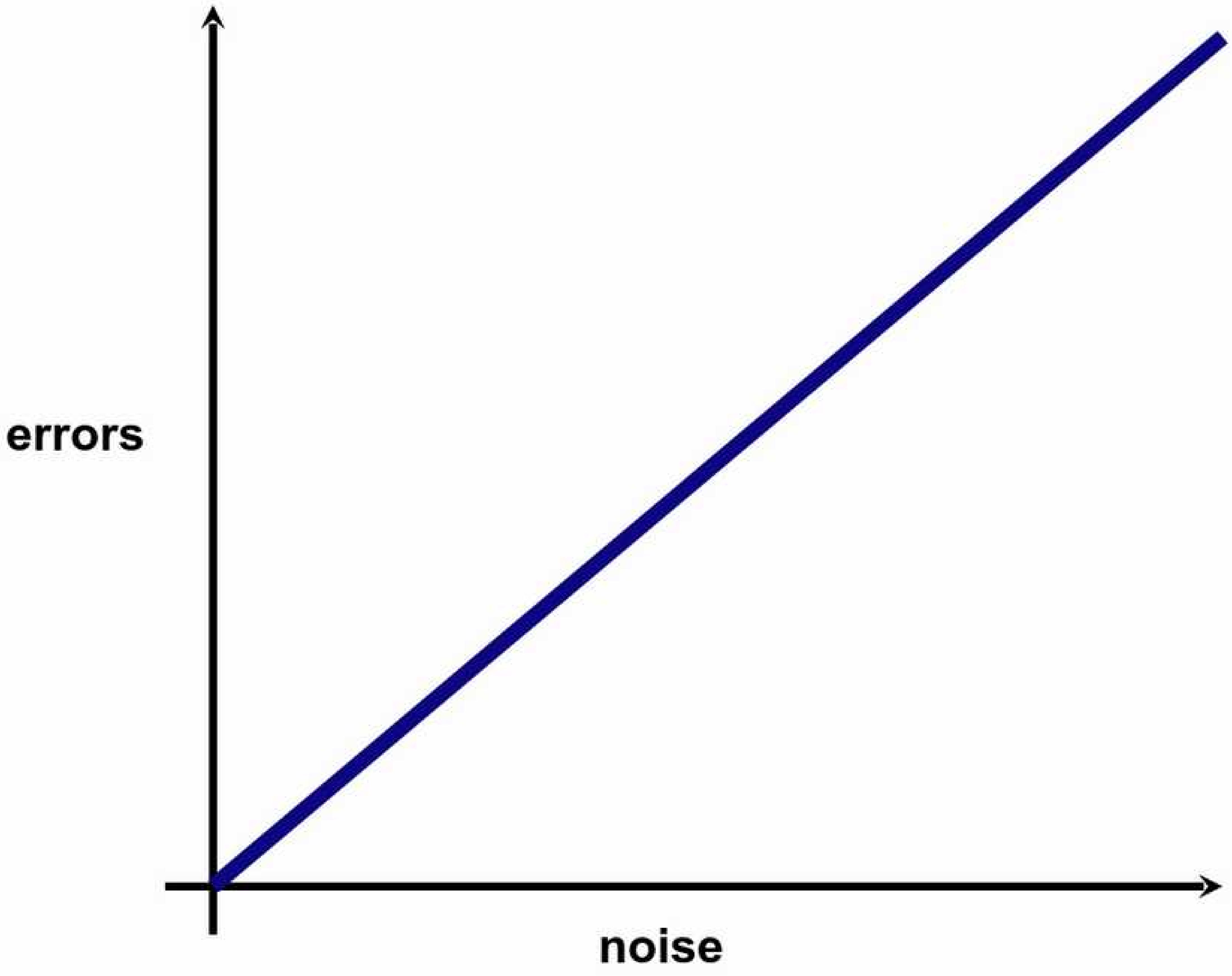
$3\varepsilon^2$

$$3(3\varepsilon^2)^2 = 1/3(3\varepsilon)^4$$

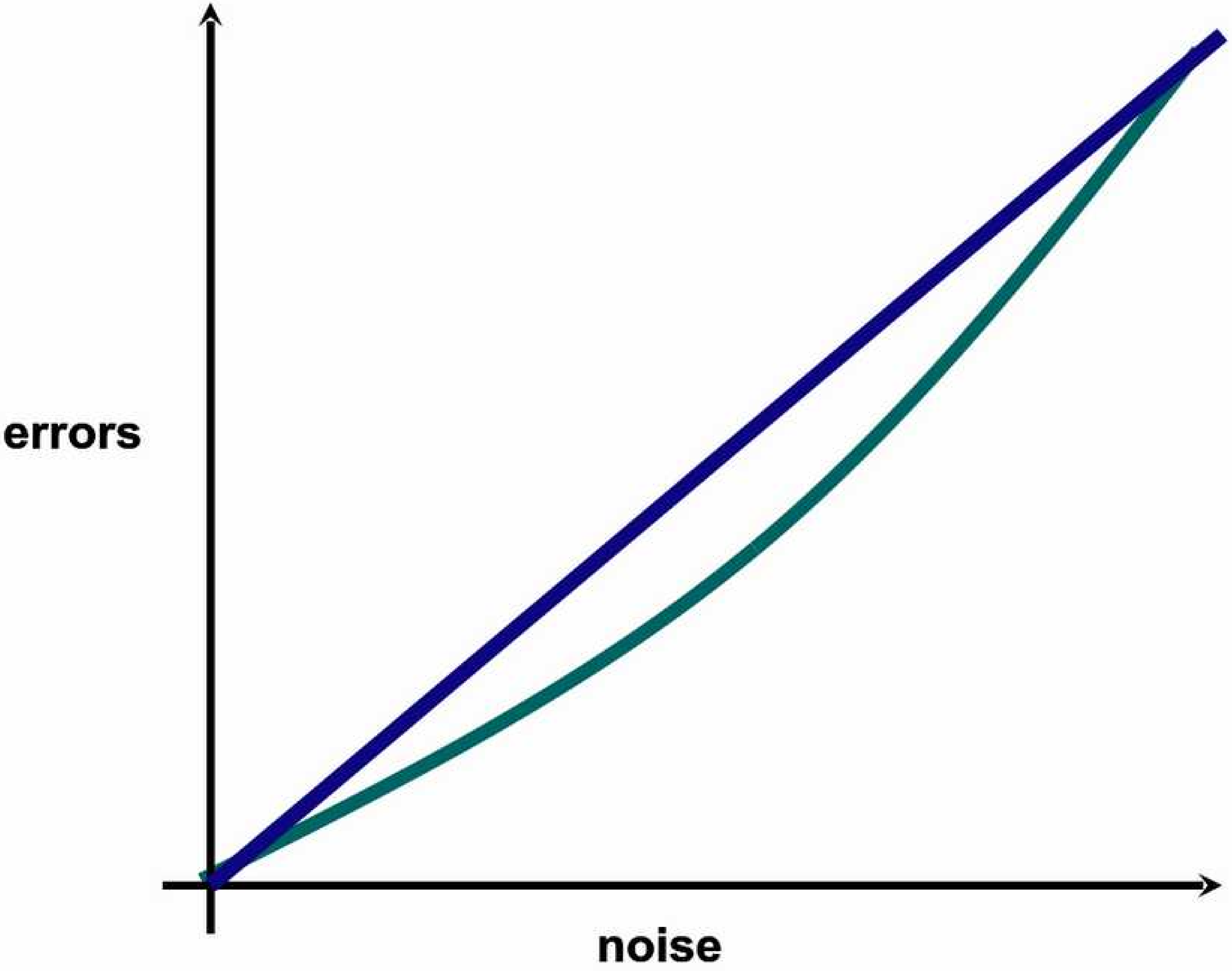
3^n

$1/3(3\varepsilon)^{2^n}$

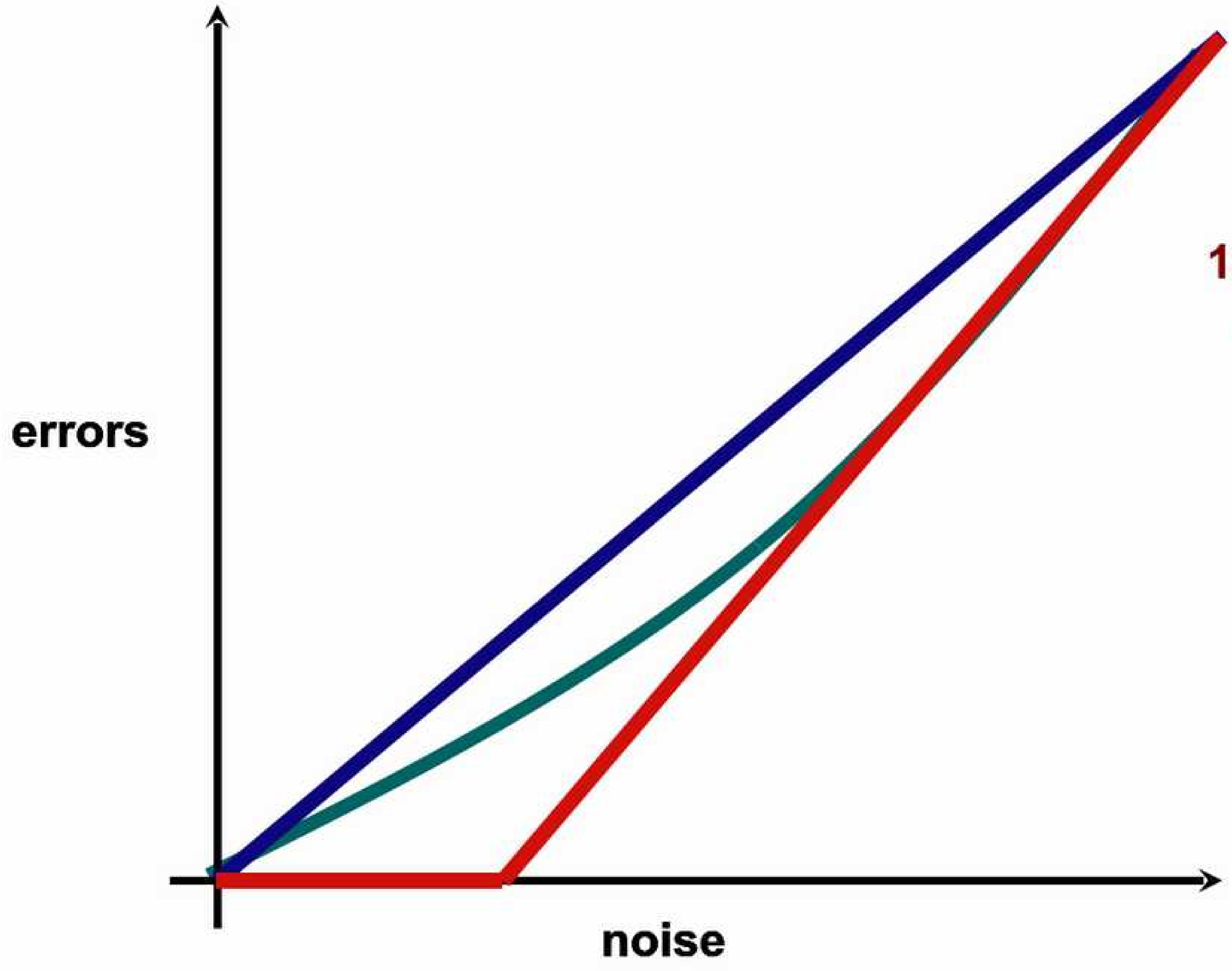
Thresholds



Thresholds

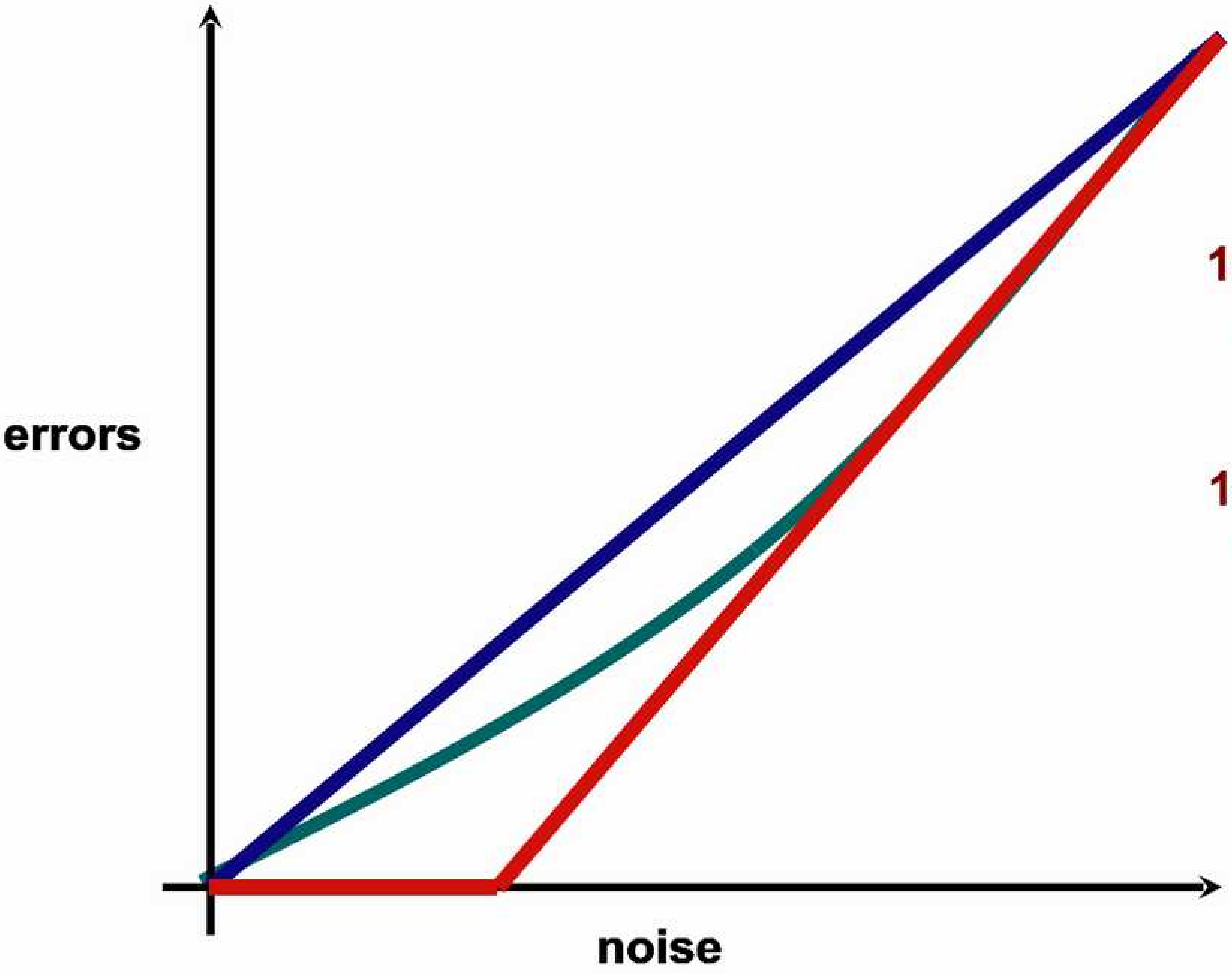


Thresholds



1940s: Communications
(Shannon)

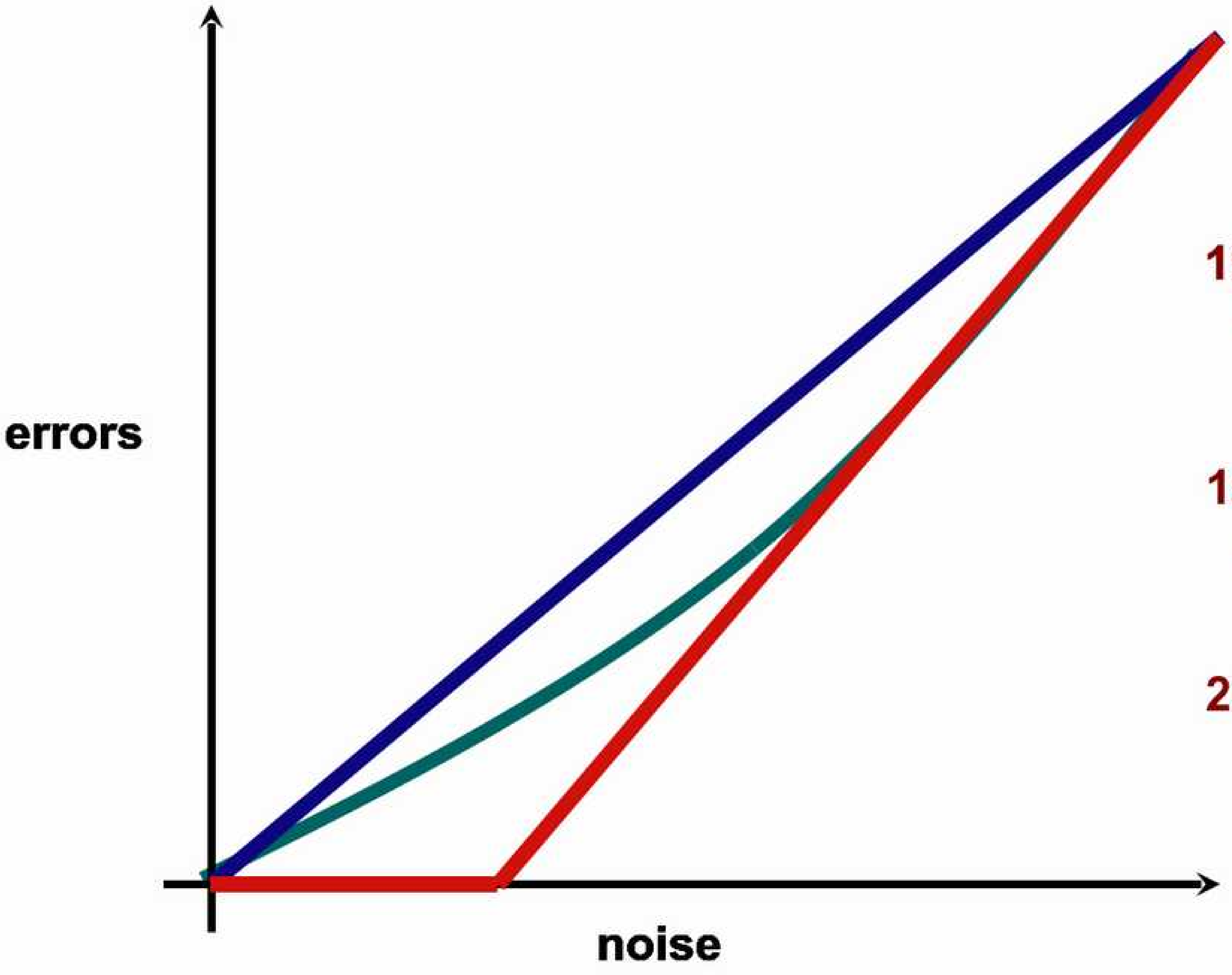
Thresholds



1940s: Communications
(Shannon)

1950s: Computation
(Winograd, von Neuma

Thresholds



1940s: Communications
(Shannon)

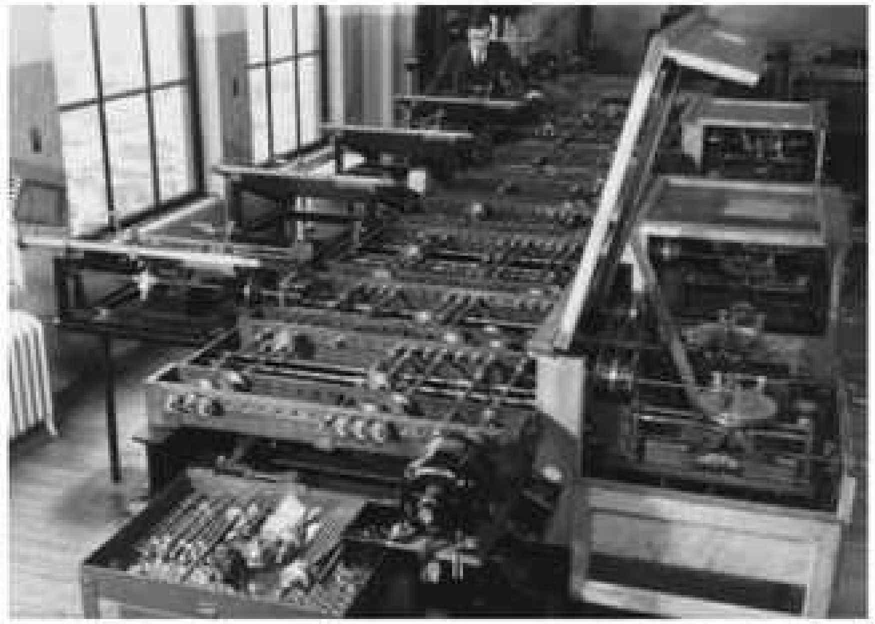
1950s: Computation
(Winograd, von Neuma

2000s: Fabrication

Digital Revolutions

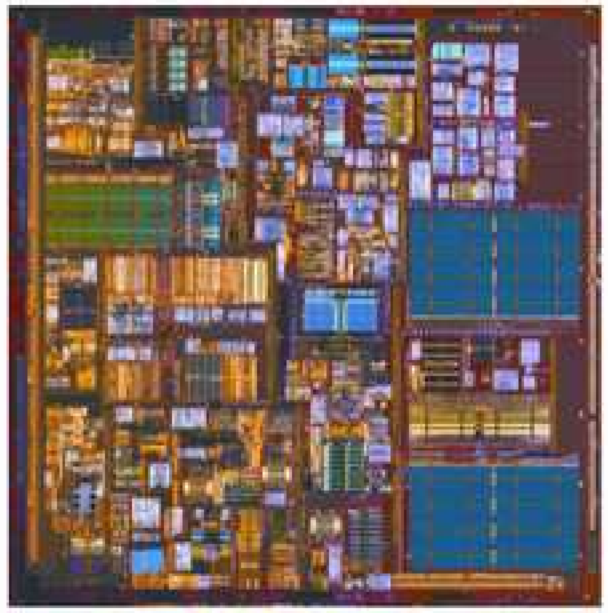
analog → digital communication

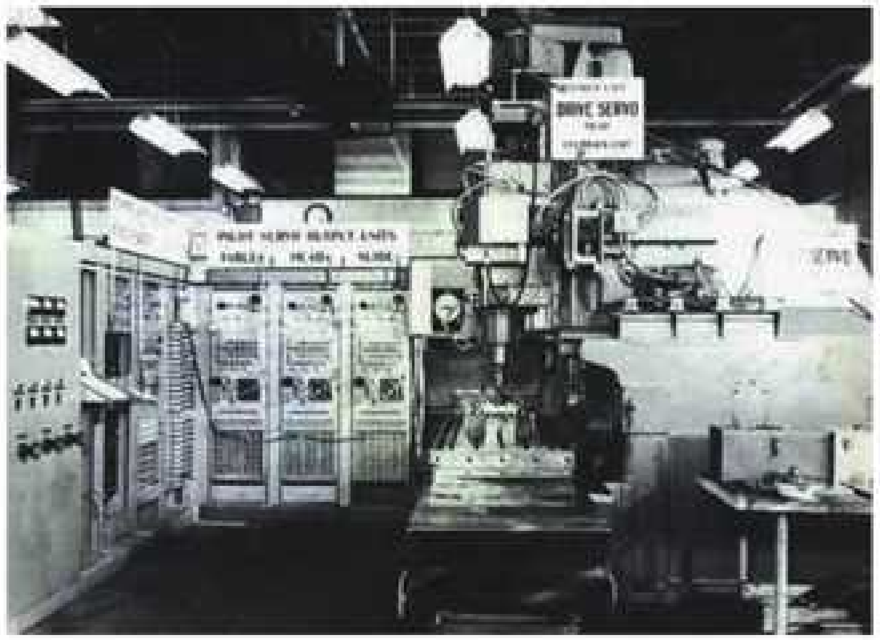
~1945



analog → digital computation

~1955





analog → digital fabrication

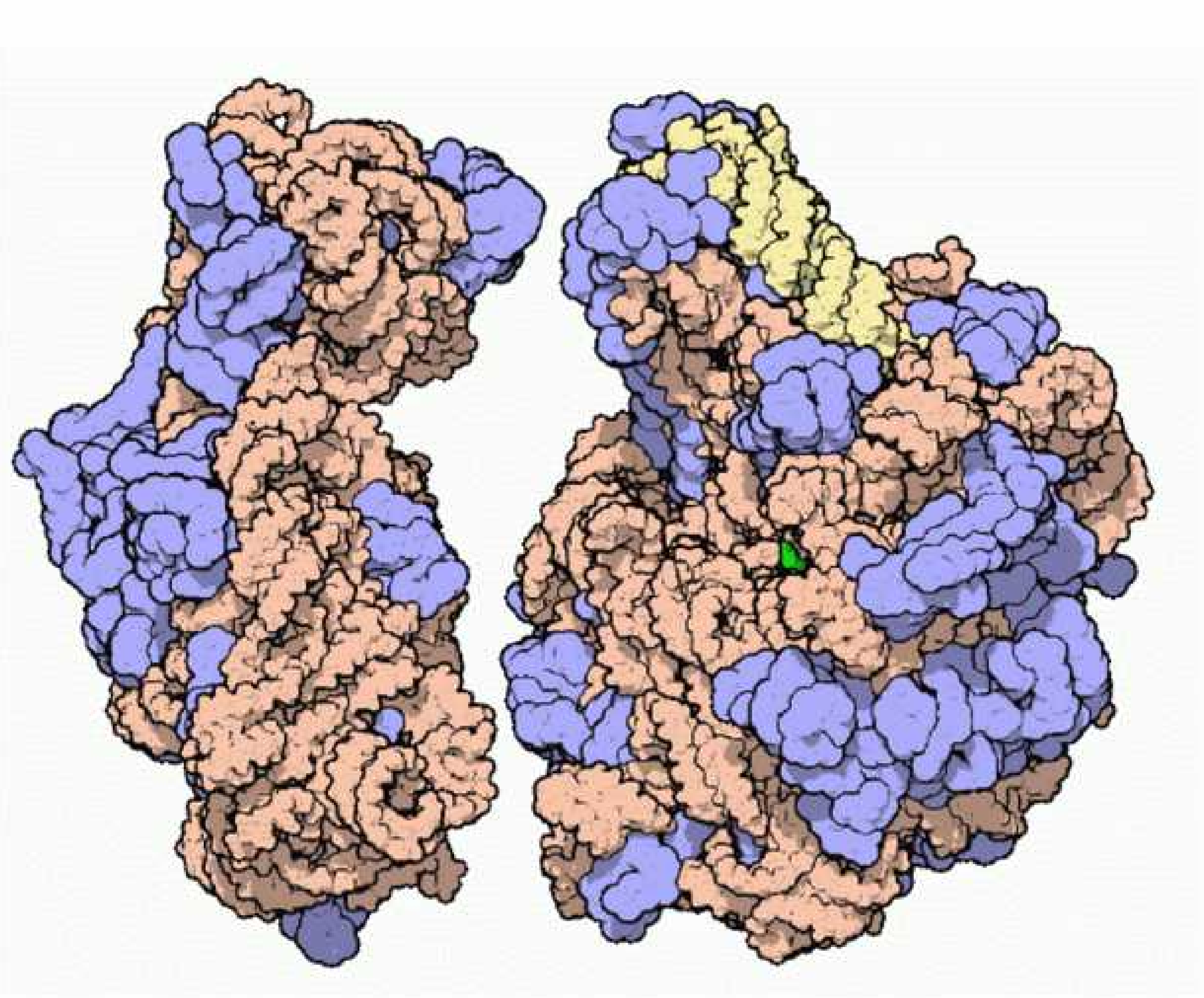
~2005

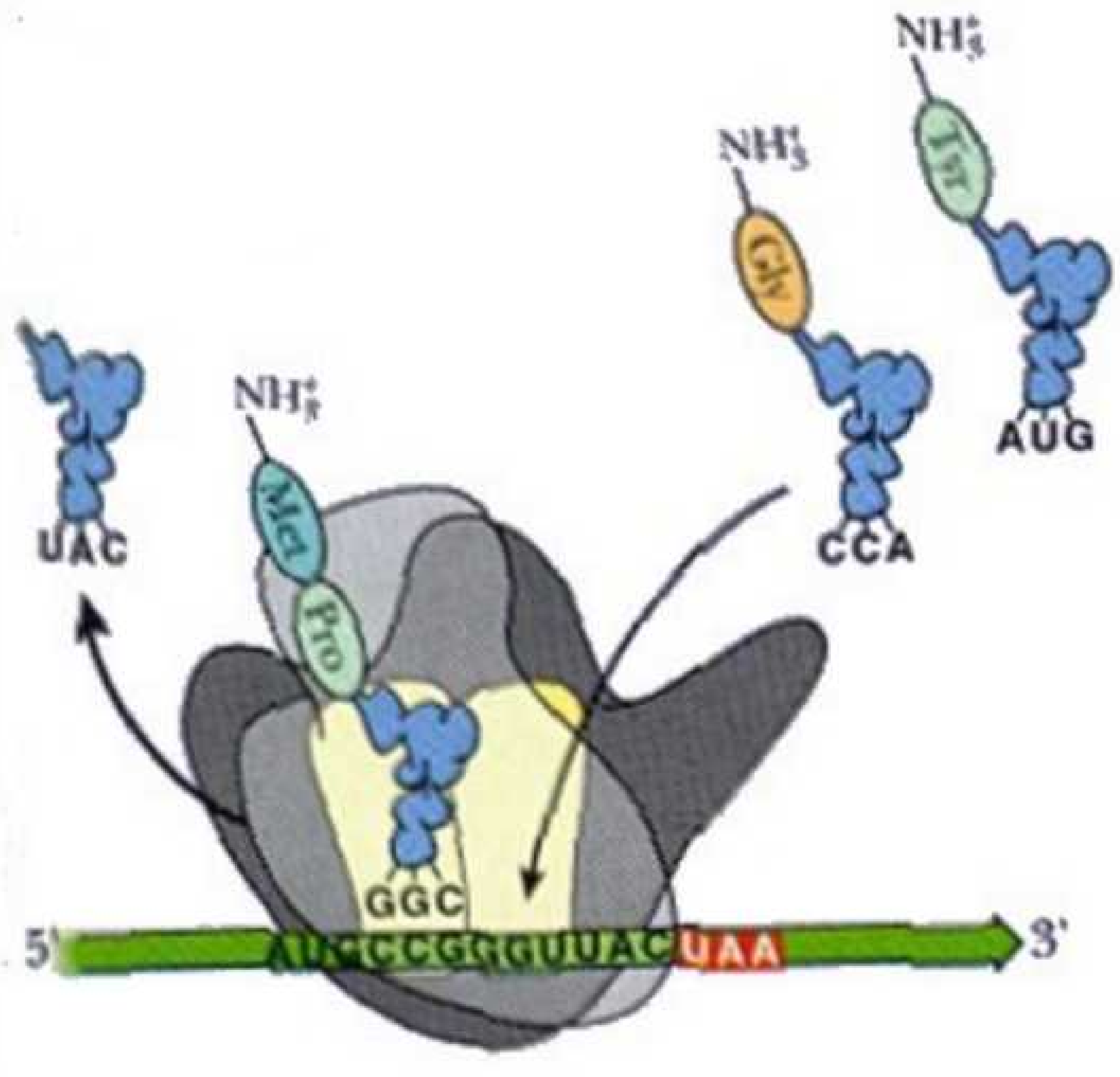
Vol 457|19 February 2009|**doi:10.1038/nature07749** nature

A hierarchical model for evolution of 23S ribosomal RNA

Konstantin Bokov[1] & Sergey V. Steinberg[1]

The emergence of the ribosome constituted a pivotal step in the evolution of life. This event happened nearly four billion years ago, and any traces of early stages of ribosome evolution are generally thought to have completely eroded away. Surprisingly, a detailed analysis of the structure of the modern ribosome reveals a concerted and modular scheme of its early evolution.



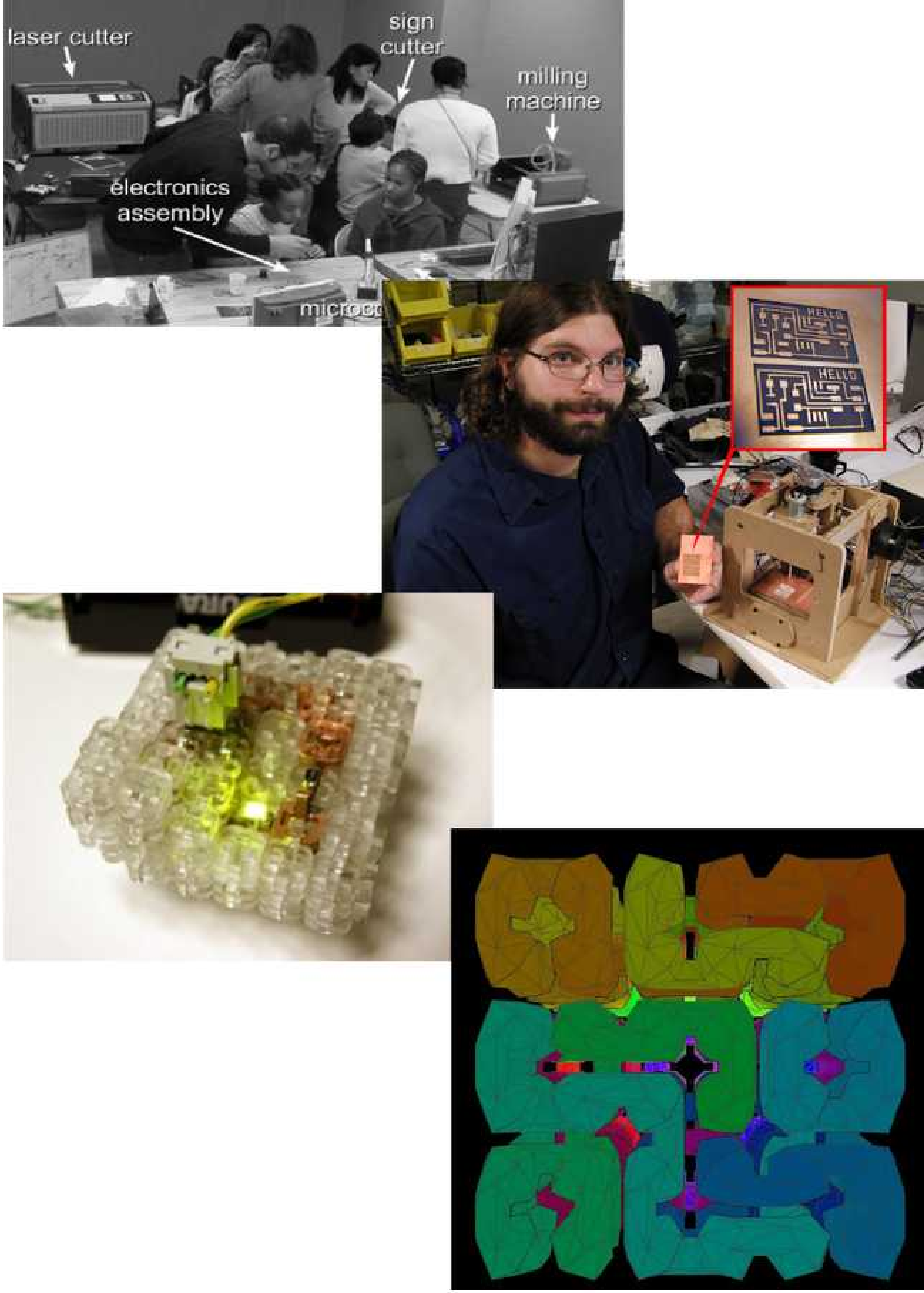


1.0: computers → machines

2.0: machines → machines

3.0: codes → materials

4.0: programs → materials



http://mtm.cba.mit.edu/

machines that make

themselves • other machines • functional parts • fun stuff

POPFAB

the portable fabrication multi-tool

designed and built by Ilan Moyer & Nadya Peek

with the MIT CADLab
MIT Center for Bits and Atoms

in collaboration with The Little Devices Lab @ MIT

The Othermill: Custom Circuits at Your Fingertips

by Otherfab

465
backers

$220,060
pledged of $50,000 goal

11
days to go

This project will be funded on Tuesday Jun 4, 3:45pm EDT.

Funding period
May 5, 2013 - Jun 4, 2013 (30 days)

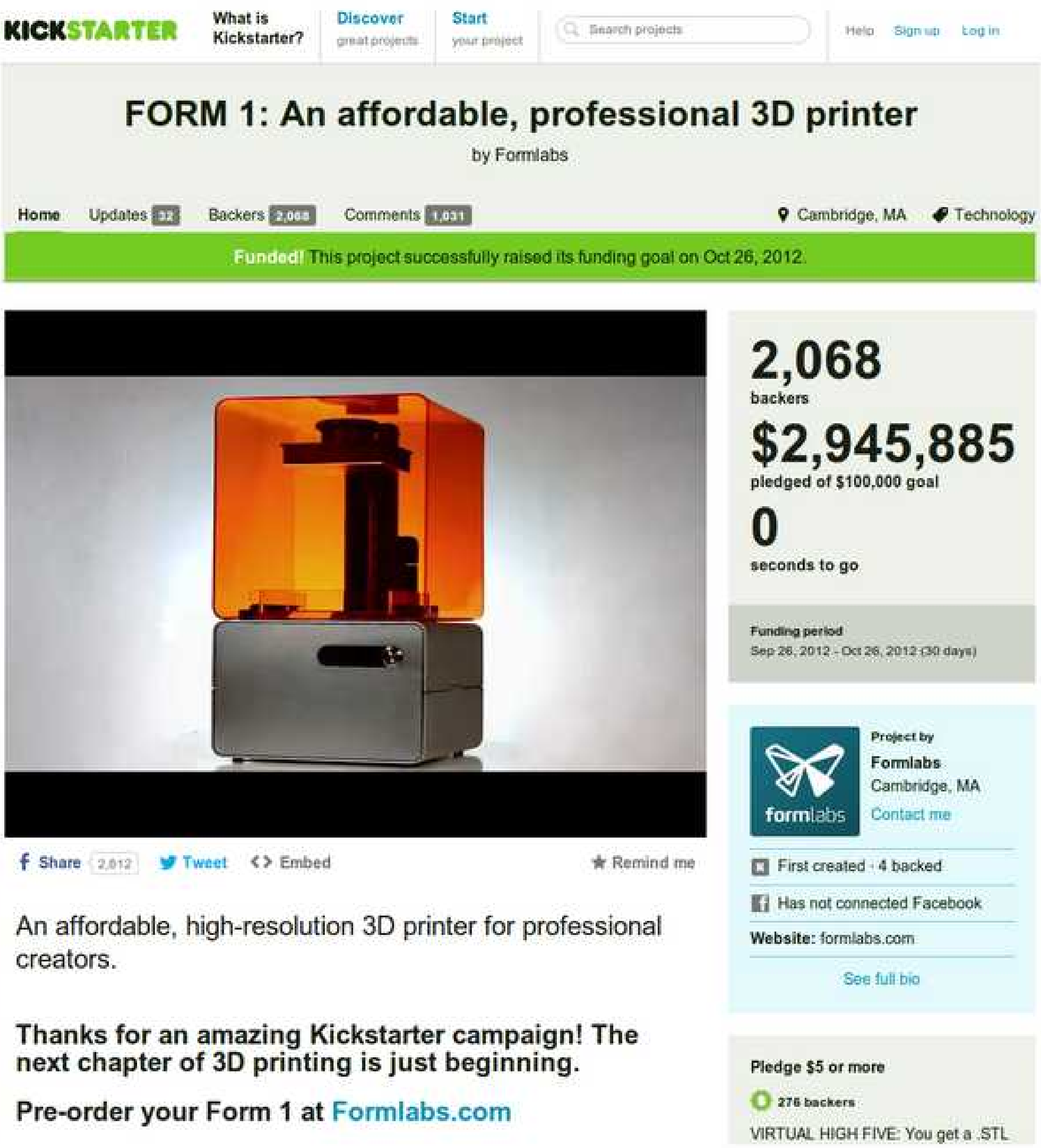
An easy to use, affordable, computer controlled mill. Take all your DIY projects further with custom circuits and precision machining.

At Otherfab, we are interested in portable, accessible, computer-controlled machines, and how they can help us design our world. With the ability to make custom circuitry, we can now build our own smart objects - medicine bottles that email reminders, shoes that tell you how fast you went, and even glasses that know when you need to put on sunscreen. The Othermill is our contribution to custom circuit design and the desktop manufacturing revolution.

Project by
Otherfab
San Francisco, CA
Contact me

First created · 1 backed
Has not connected Facebook
Website: otherfab.com

See full bio



FORM 1: An affordable, professional 3D printer

by Formlabs

Funded! This project successfully raised its funding goal on Oct 26, 2012.

2,068
backers

$2,945,885
pledged of $100,000 goal

0
seconds to go

Funding period
Sep 26, 2012 - Oct 26, 2012 (30 days)

An affordable, high-resolution 3D printer for professional creators.

Thanks for an amazing Kickstarter campaign! The next chapter of 3D printing is just beginning.

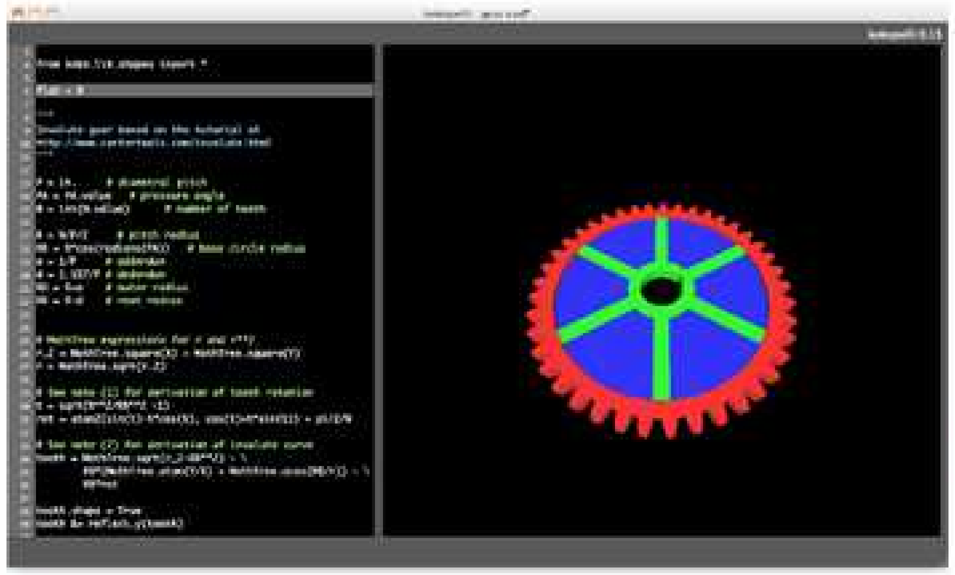
Pre-order your Form 1 at Formlabs.com

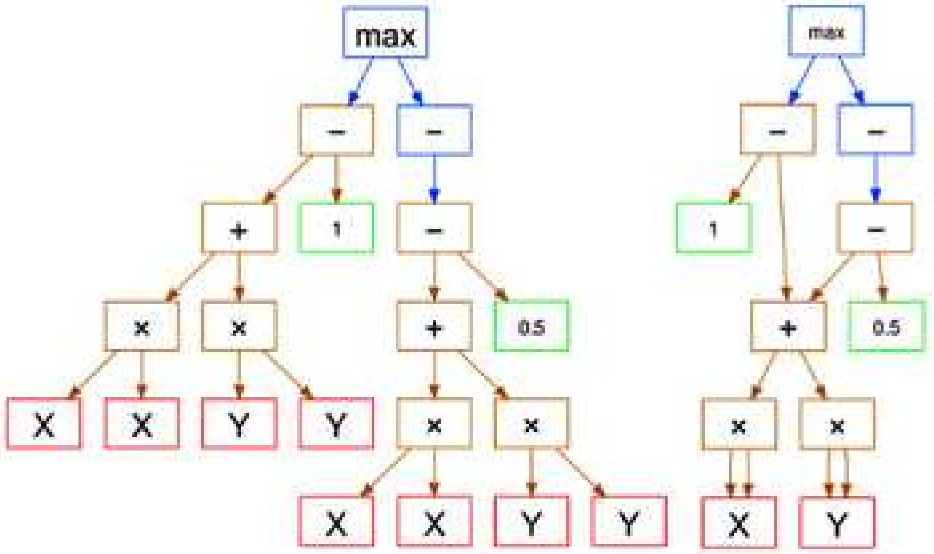
Project by
Formlabs
Cambridge, MA
Contact me

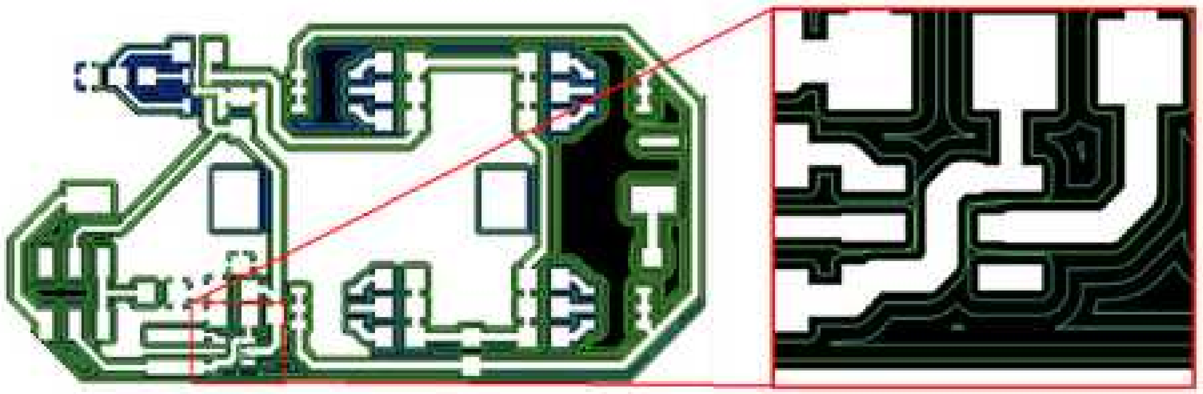
First created · 4 backed
Has not connected Facebook
Website: formlabs.com

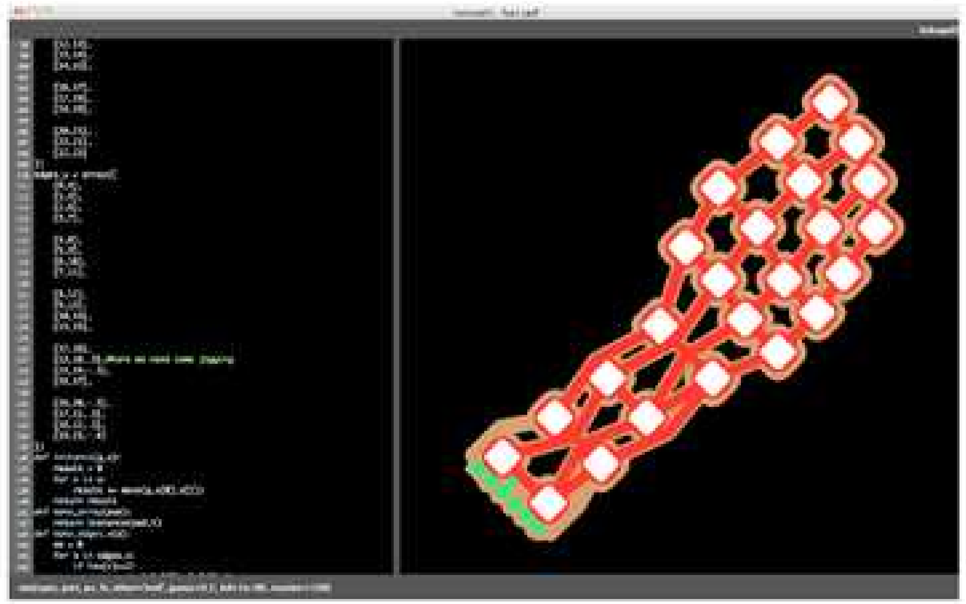
See full bio

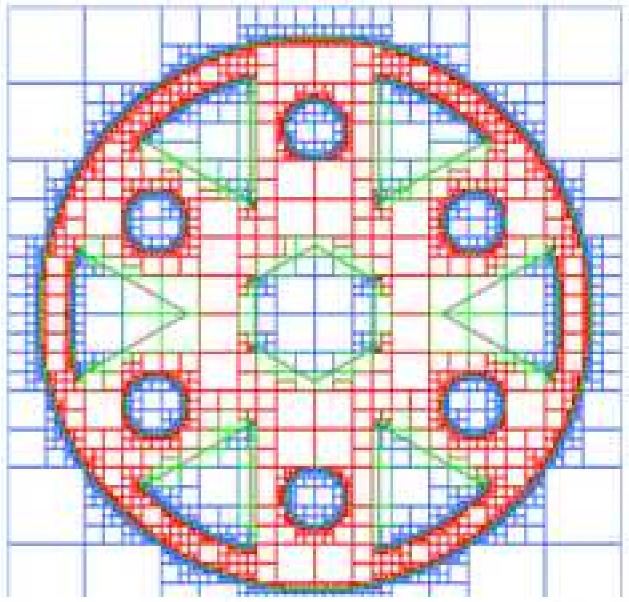
Pledge $5 or more
276 backers
VIRTUAL HIGH FIVE: You get a .STL

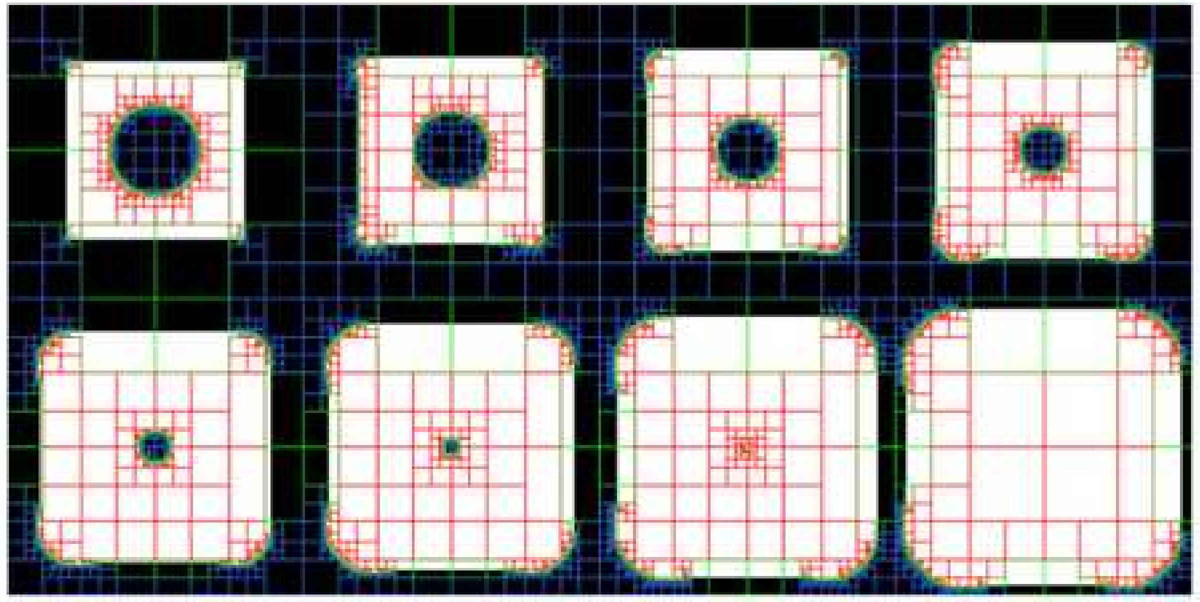


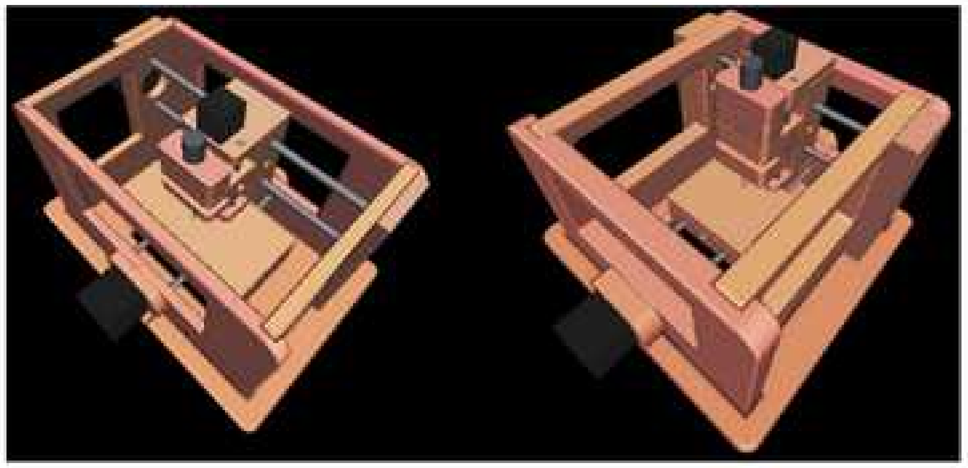


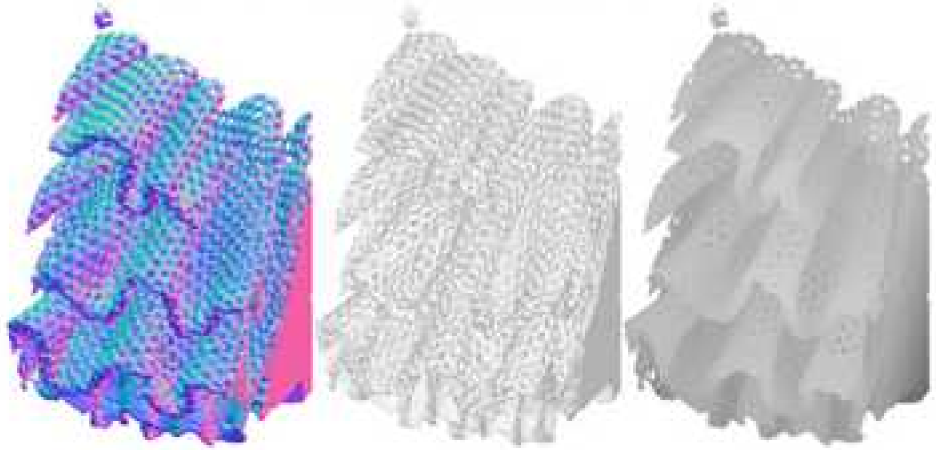


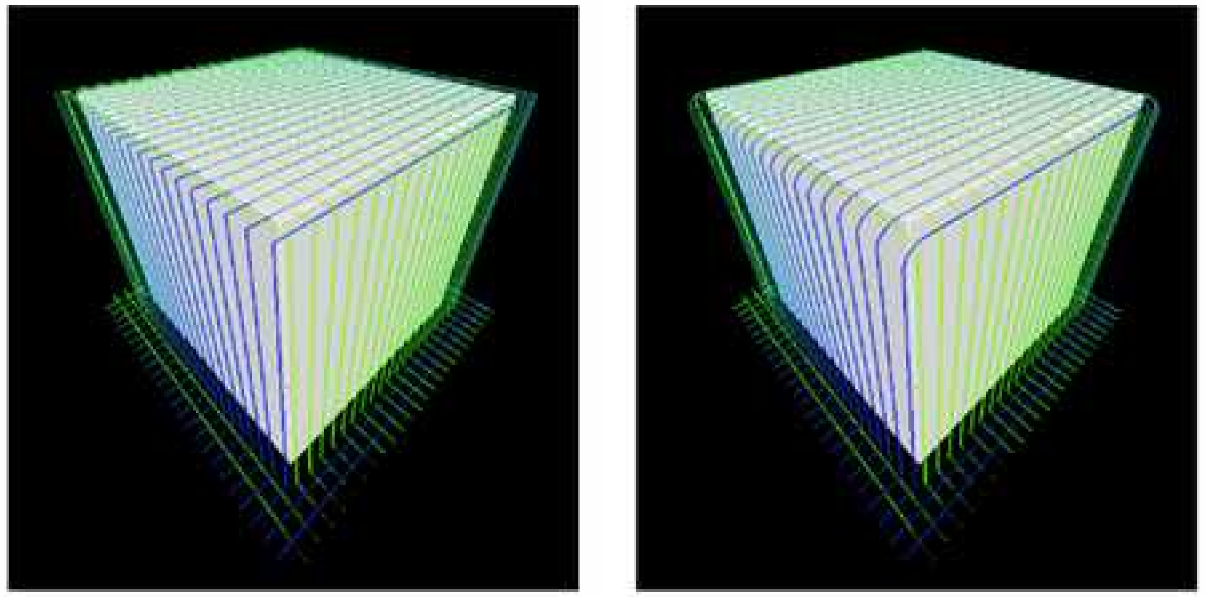




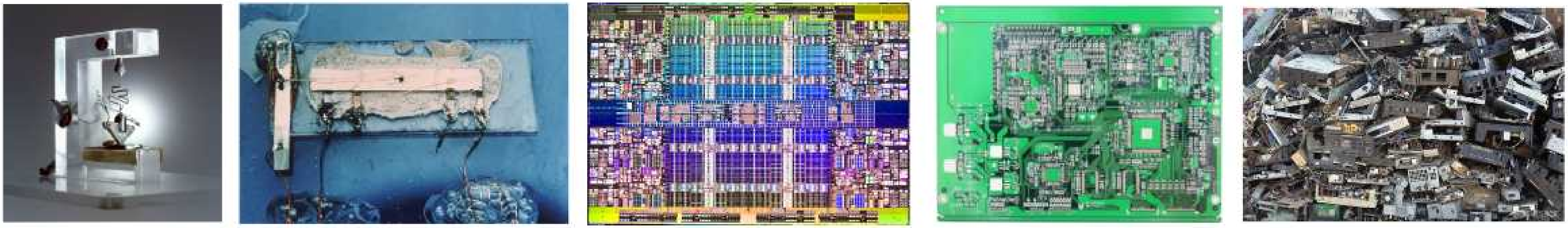


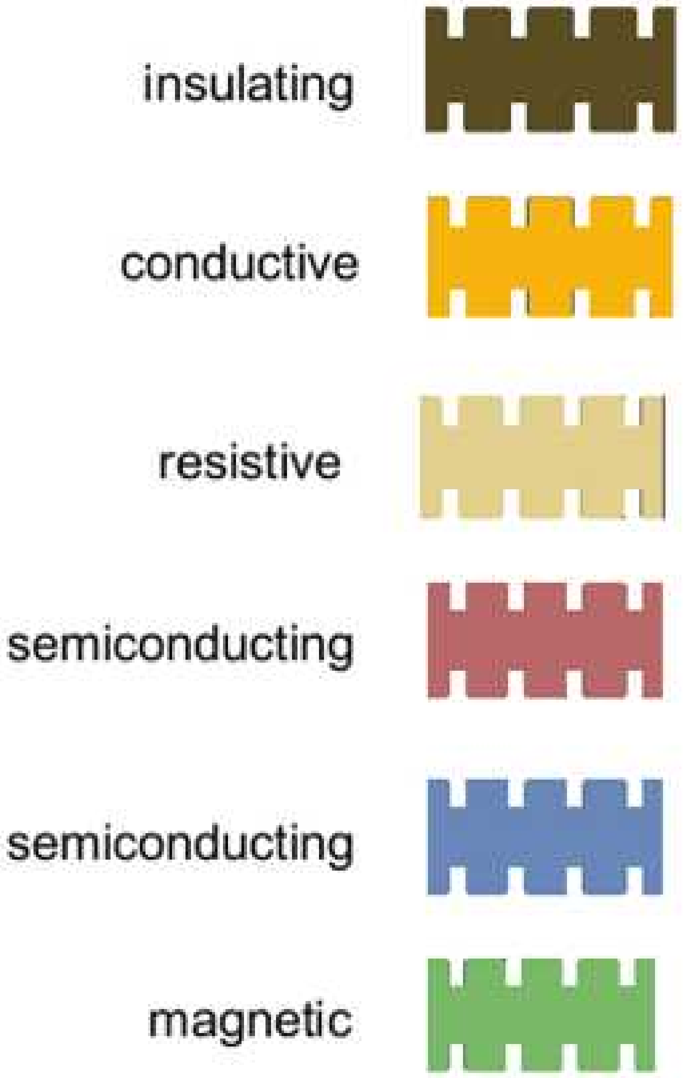


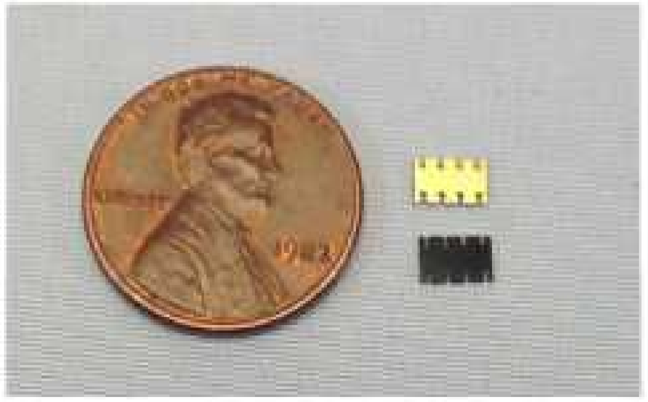


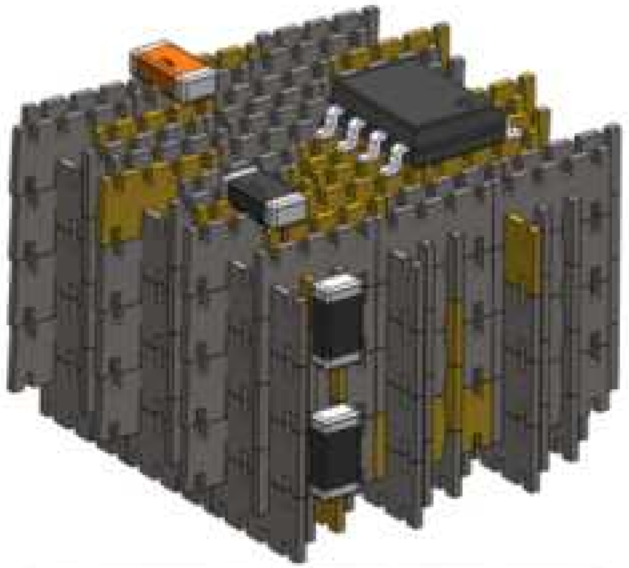


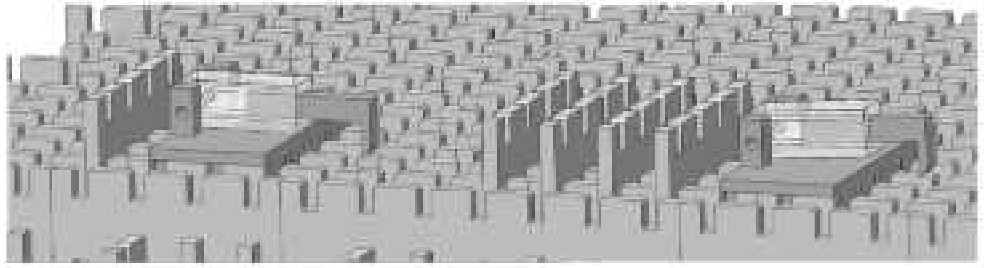
(Kokopelli: Matt Keeter)

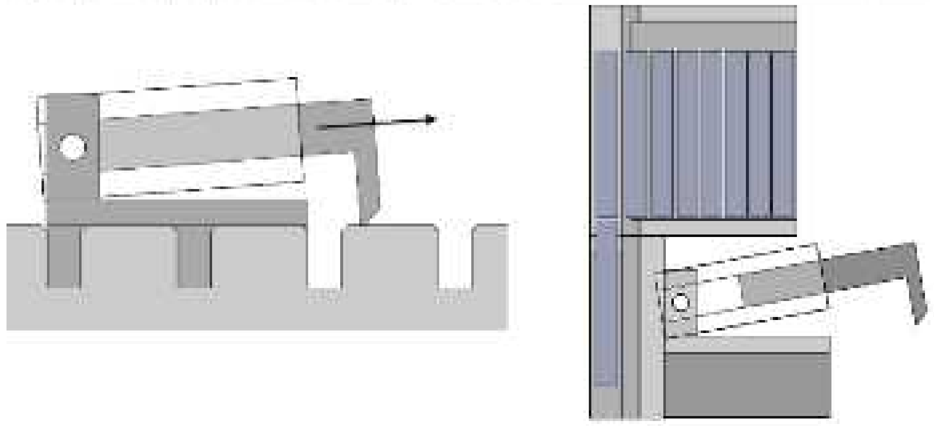


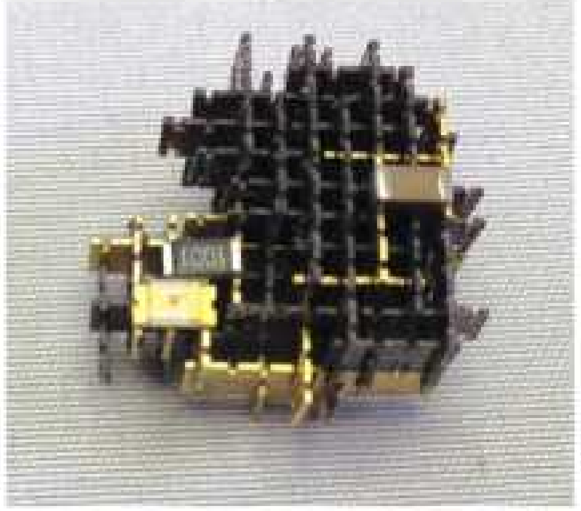


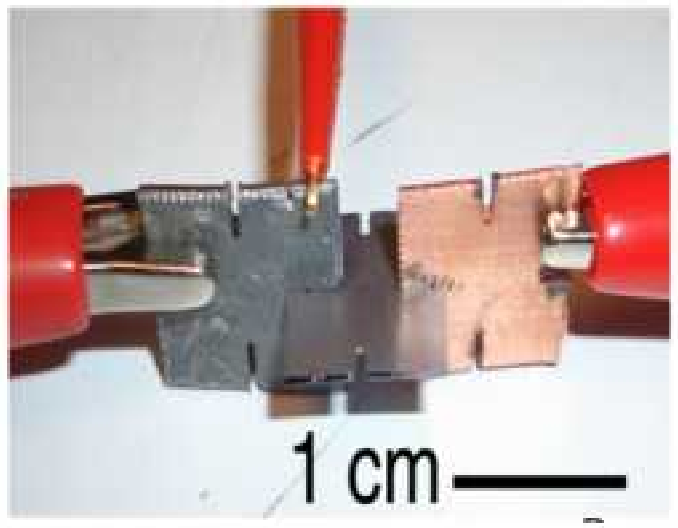


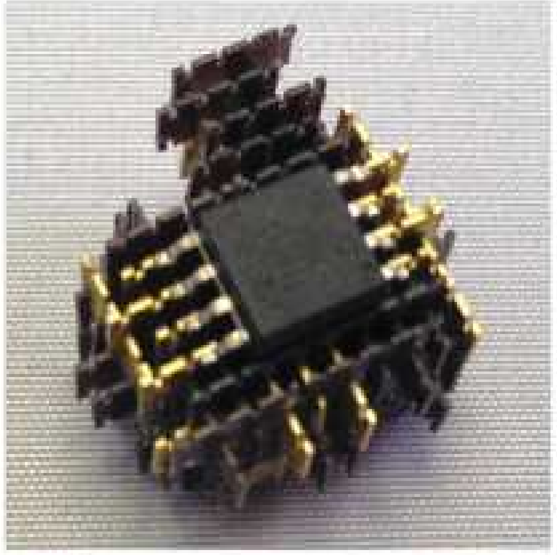


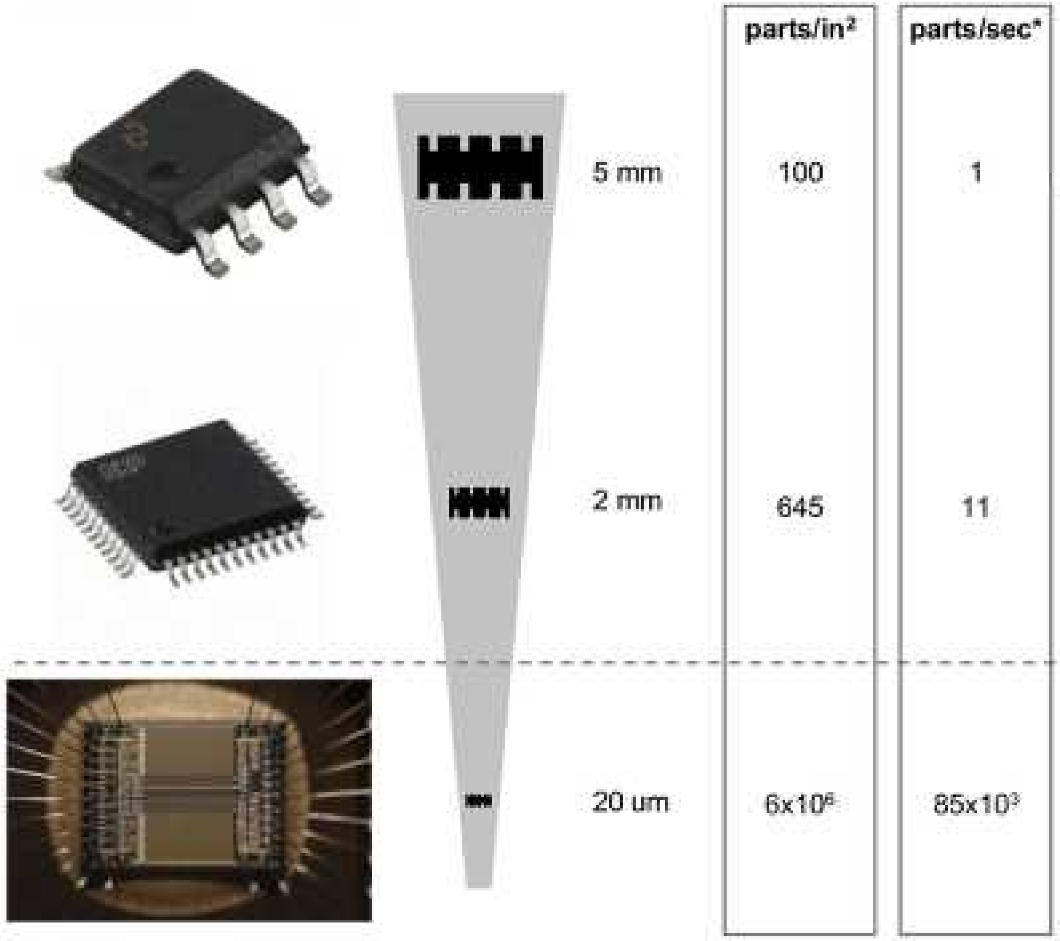












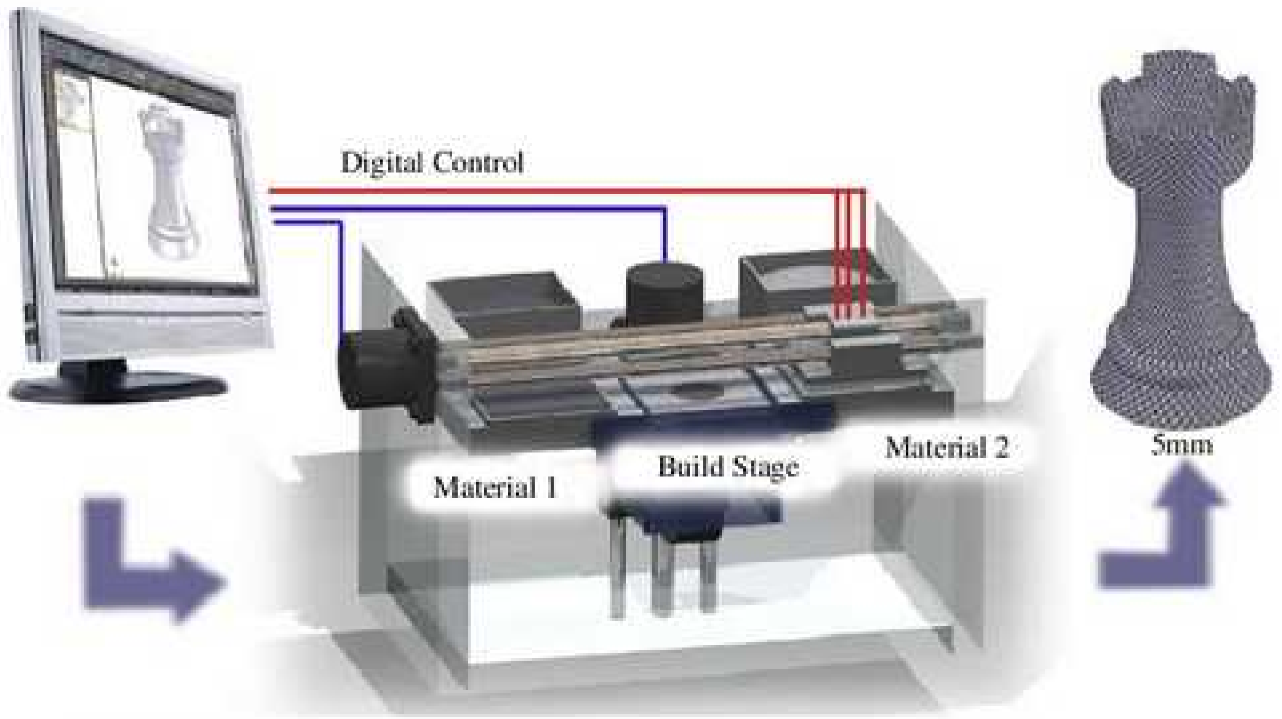
	parts/in^2	parts/sec*
5 mm	100	1
2 mm	645	11
20 um	6×10^6	85×10^3

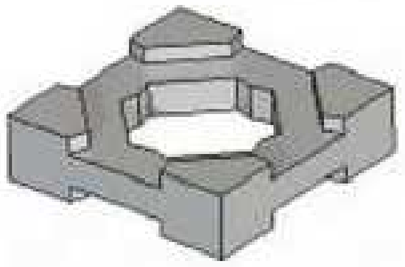
(Will Langford)

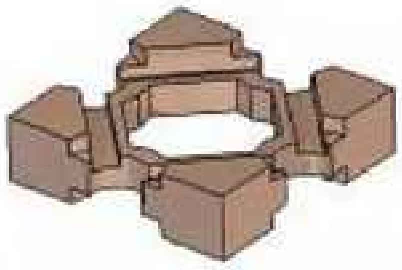
Design and analysis of digital materials for physical 3D voxel printing

Jonathan Hiller and Hod Lipson
Cornell Computational Synthesis Lab, Cornell University, Ithaca, New York, USA

Figure 1 The principle of a digital manufacturing process, using spherical voxels







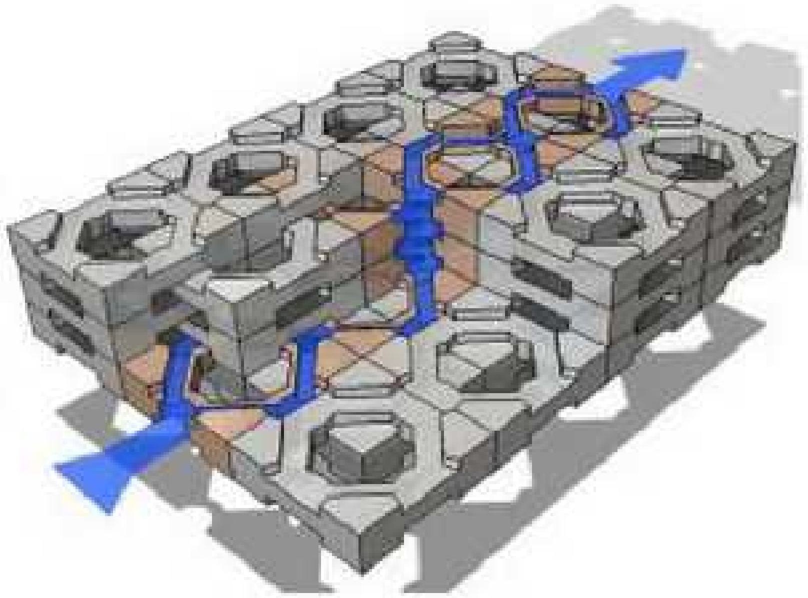
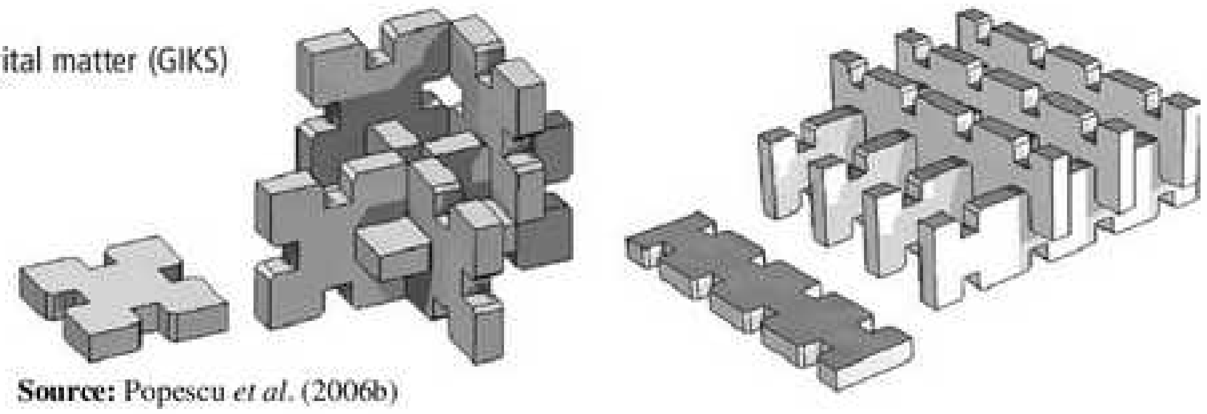
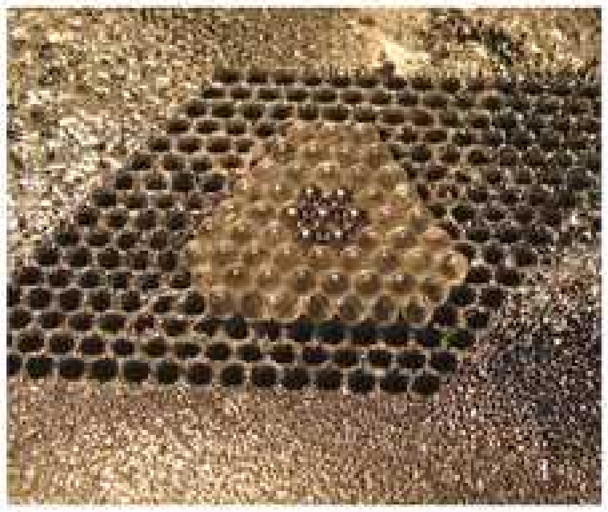
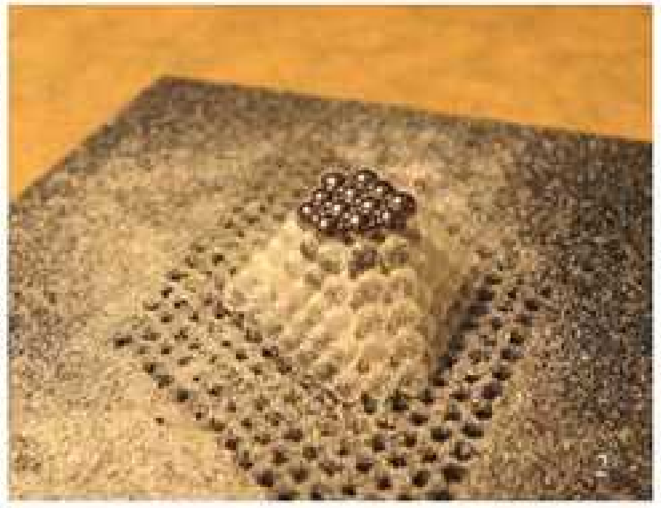


Figure 4 Sparse digital matter (GIKS)

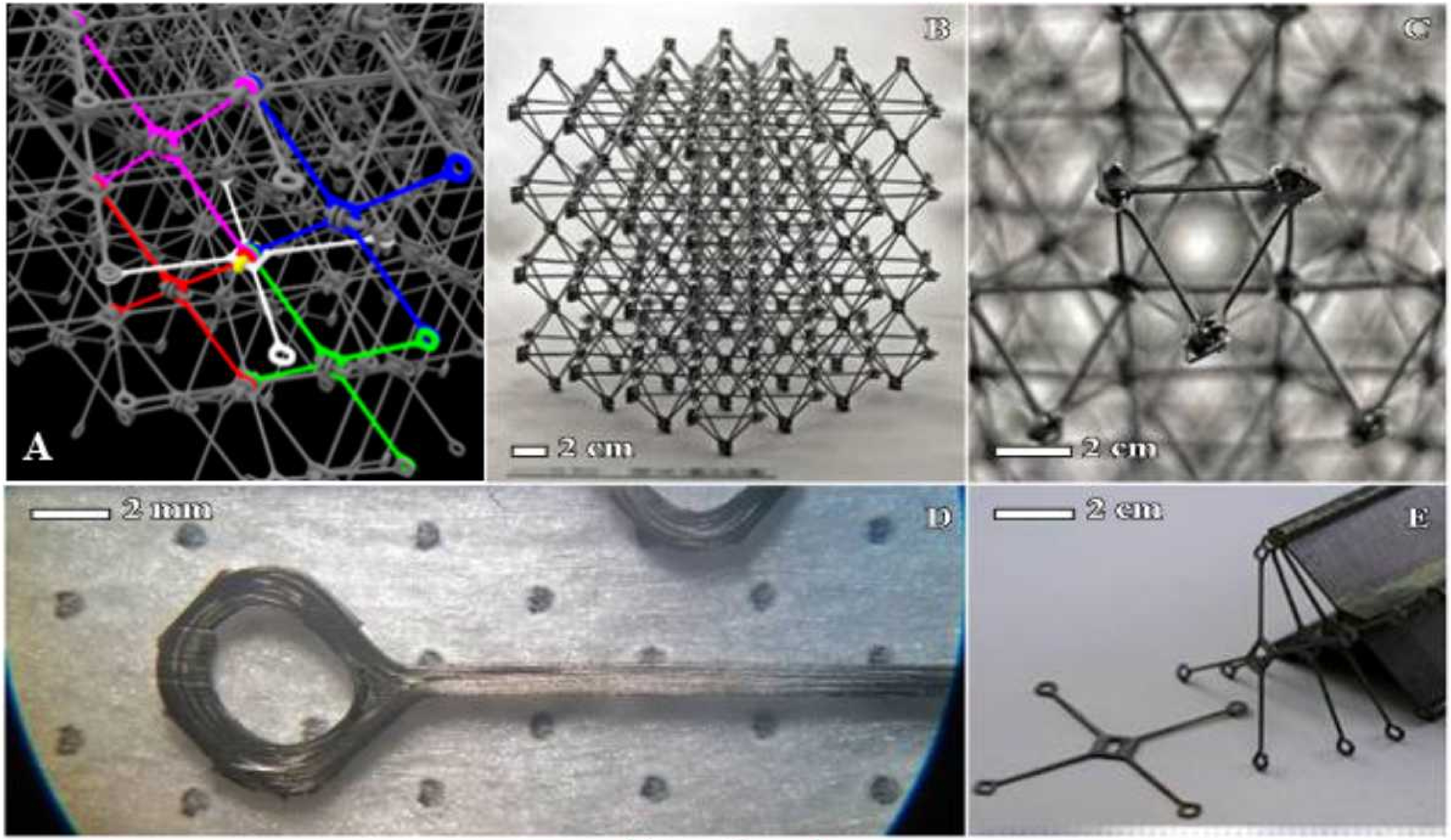


Source: Popescu *et al.* (2006b)

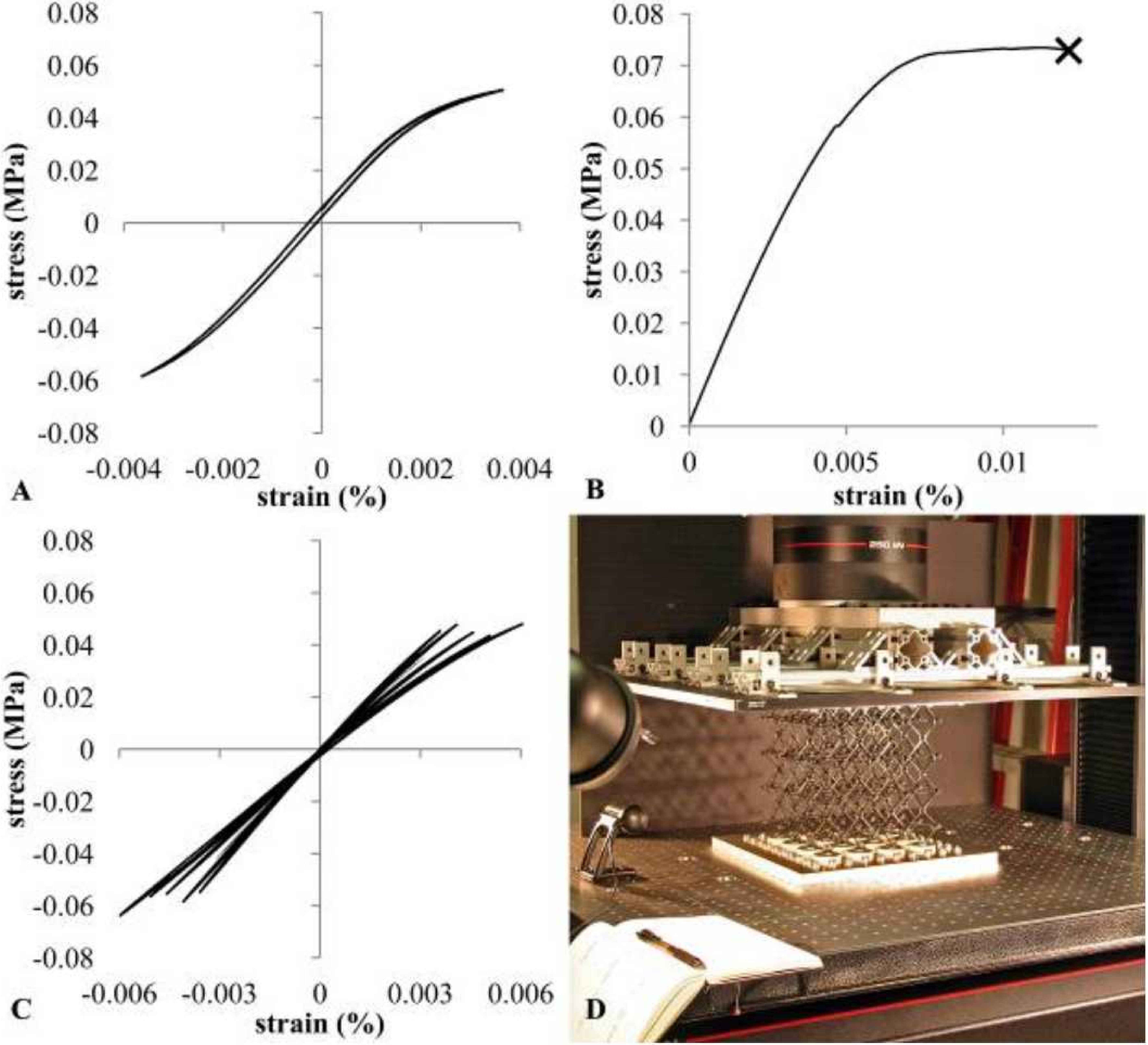


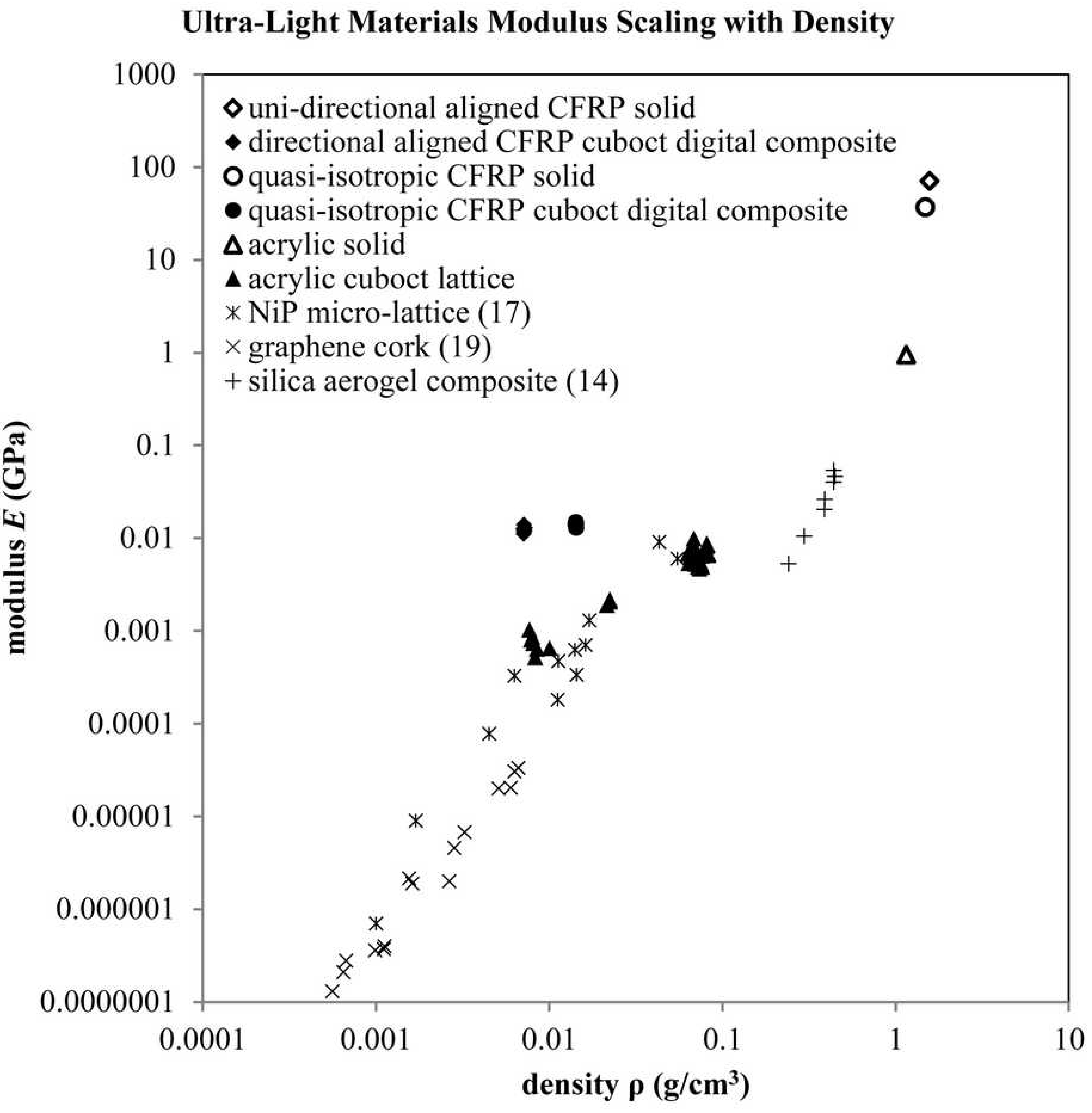


Rapid Prototyping Journal
15/2 (2009) 137–149
© Emerald Group Publishing Limited [ISSN 1355-2546]
[DOI 10.1108/13552540910943441]

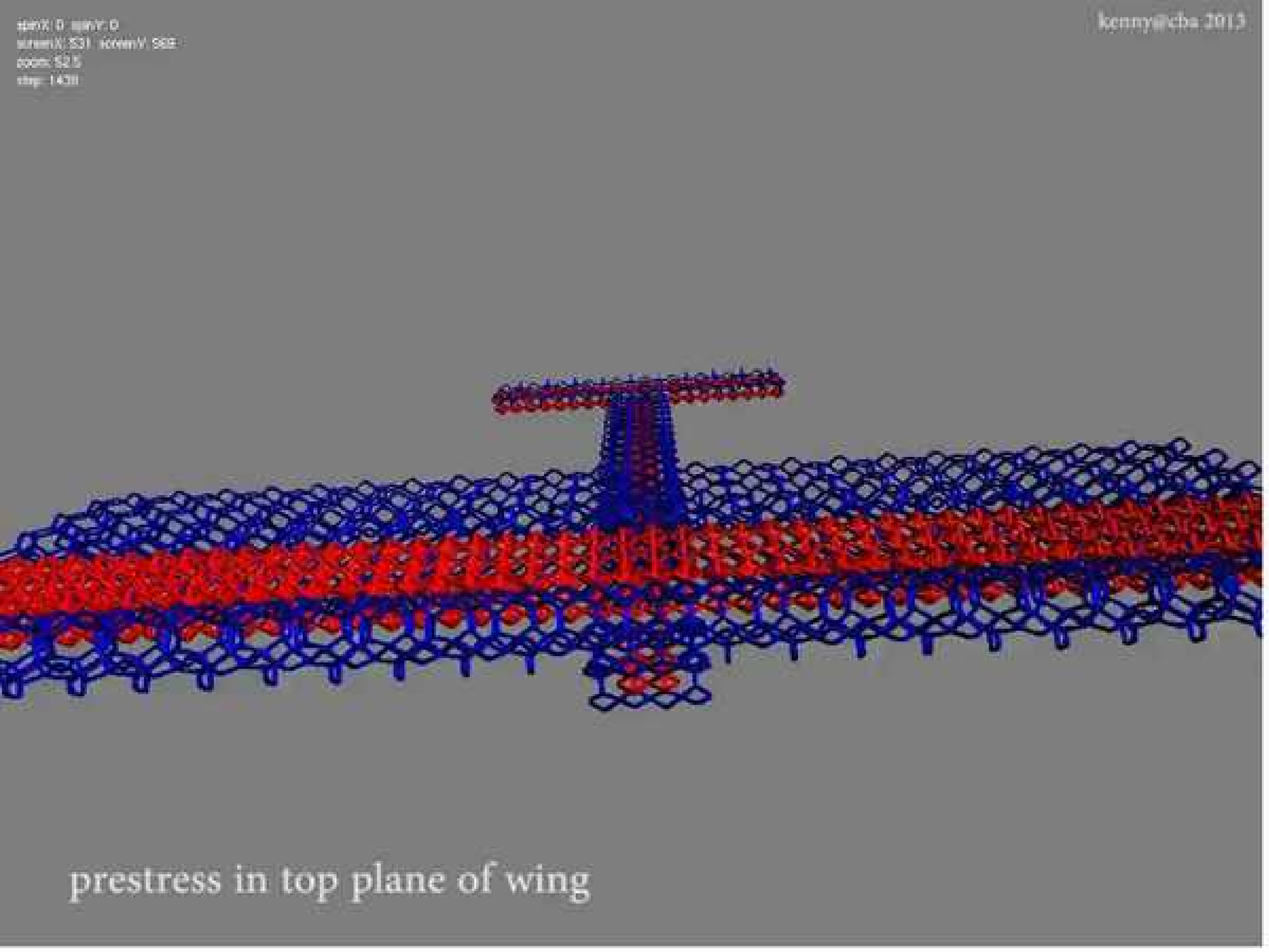


(Kenny Cheung)

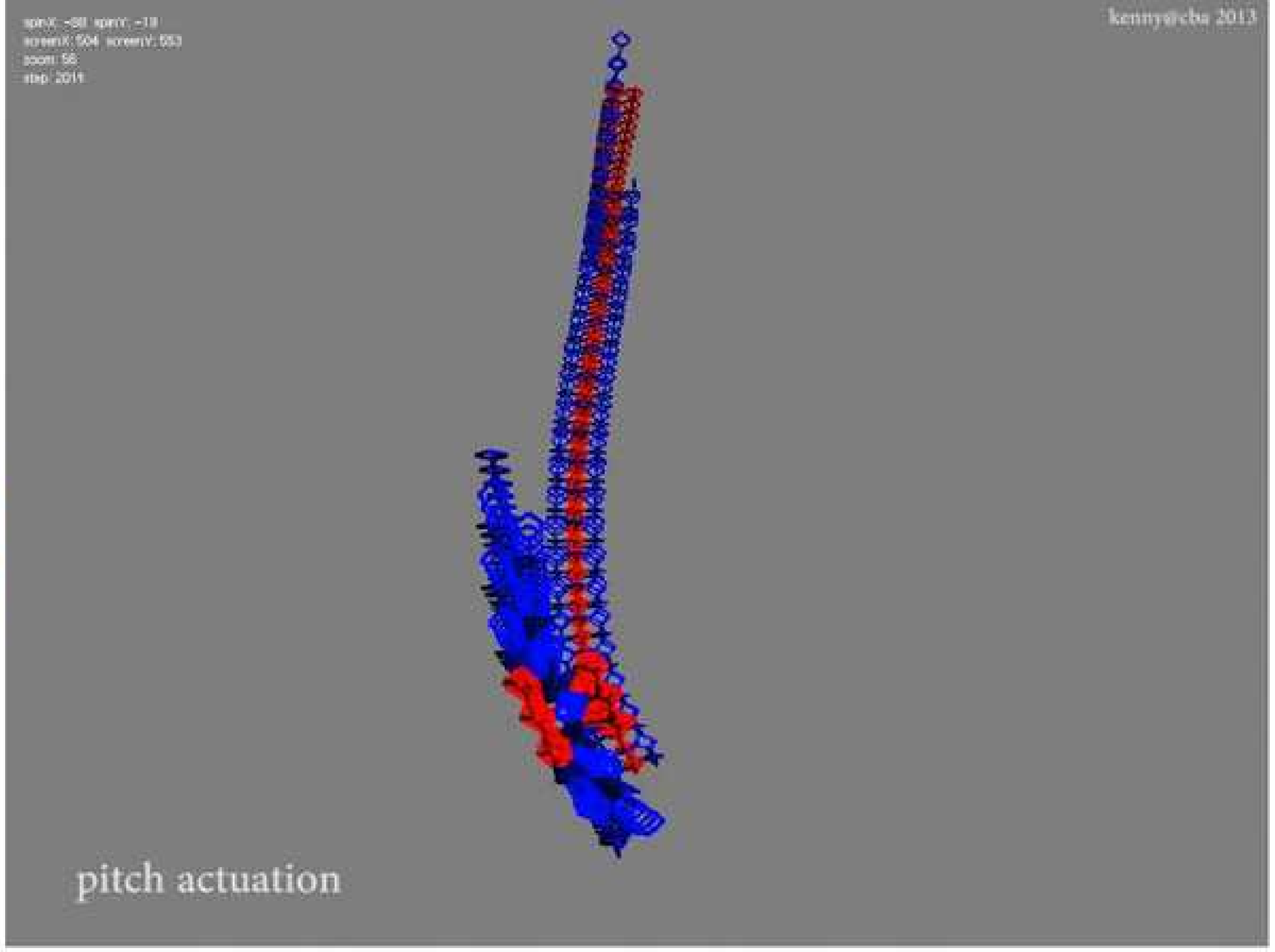

A
stress (MPa)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.004
-0.002
0
0.002
0.004
strain (%)
B
stress (MPa)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.005
0.01
strain (%)
C
stress (MPa)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.006
-0.003
0
0.003
0.006
strain (%)
D


Ultra-Light Materials Modulus Scaling with Density
◇ uni-directional aligned CFRP solid
◆ directional aligned CFRP cuboct digital composite
○ quasi-isotropic CFRP solid
● quasi-isotropic CFRP cuboct digital composite
△ acrylic solid
▲ acrylic cuboct lattice
✳ NiP micro-lattice (17)
× graphene cork (19)
+ silica aerogel composite (14)
modulus E (GPa)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
density ρ (g/cm³)
0.0001
0.001
0.01
0.1
1
10

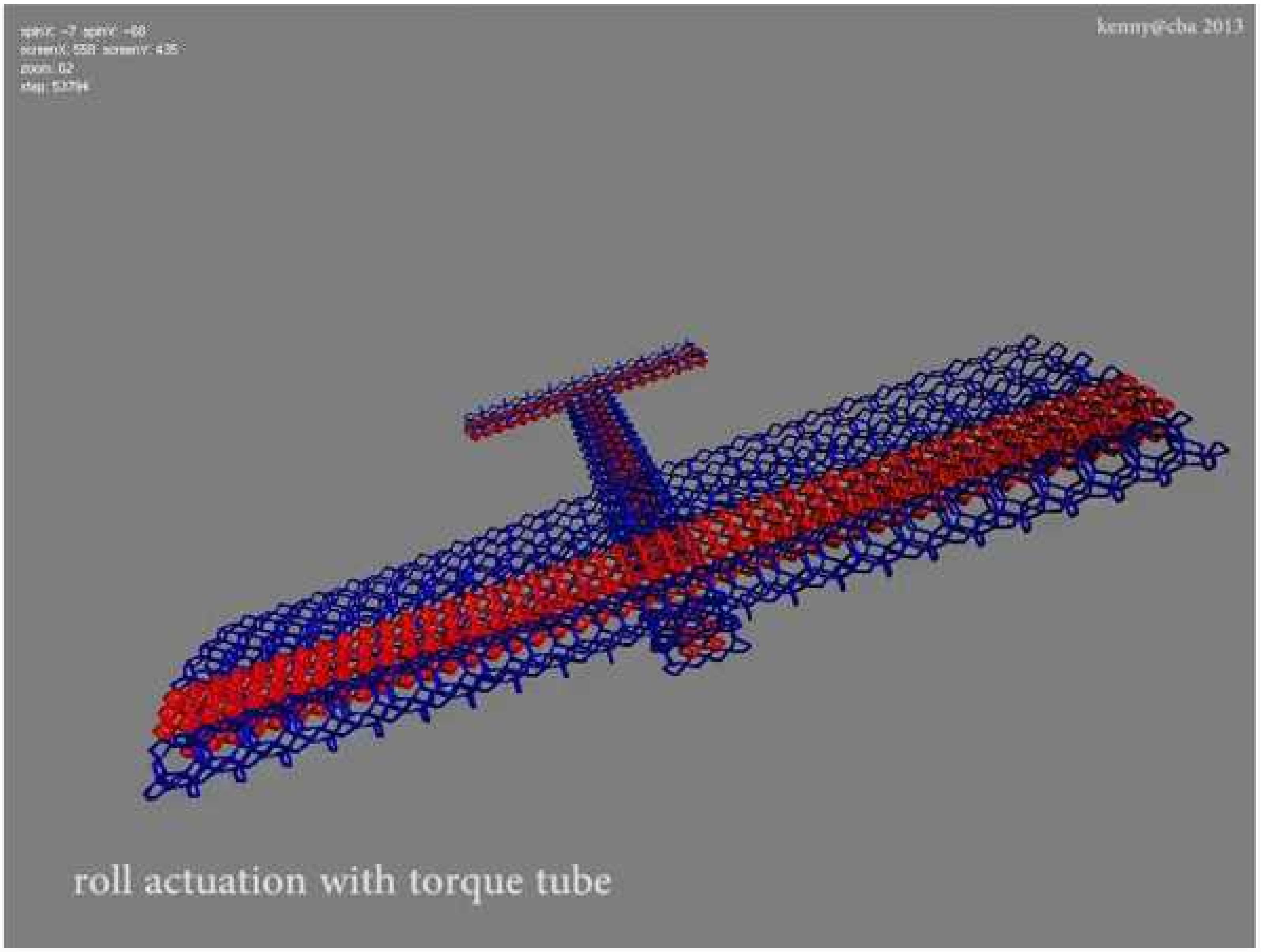
kenny@cba.mit.edu 2012



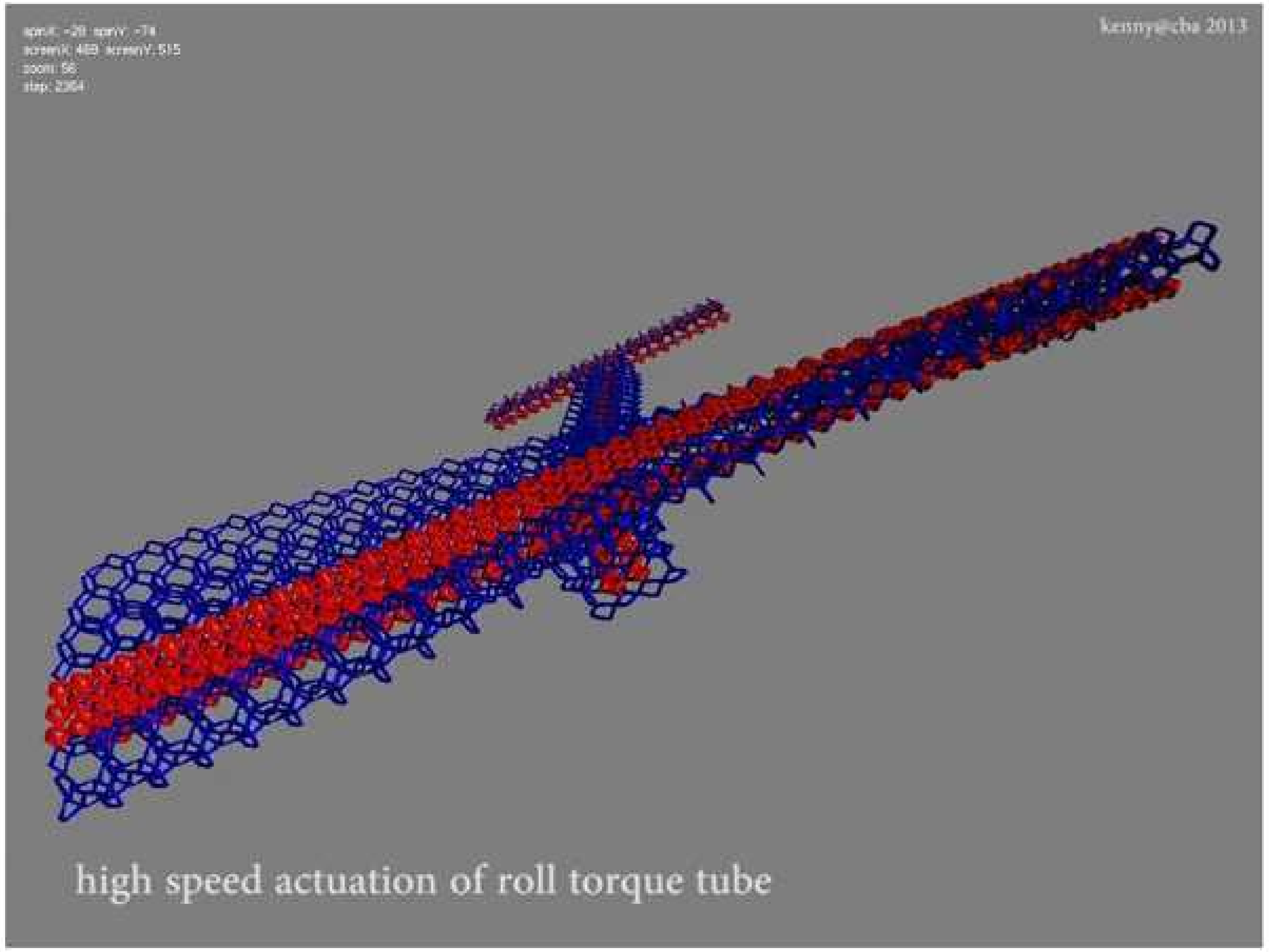
prestress in top plane of wing



pitch actuation

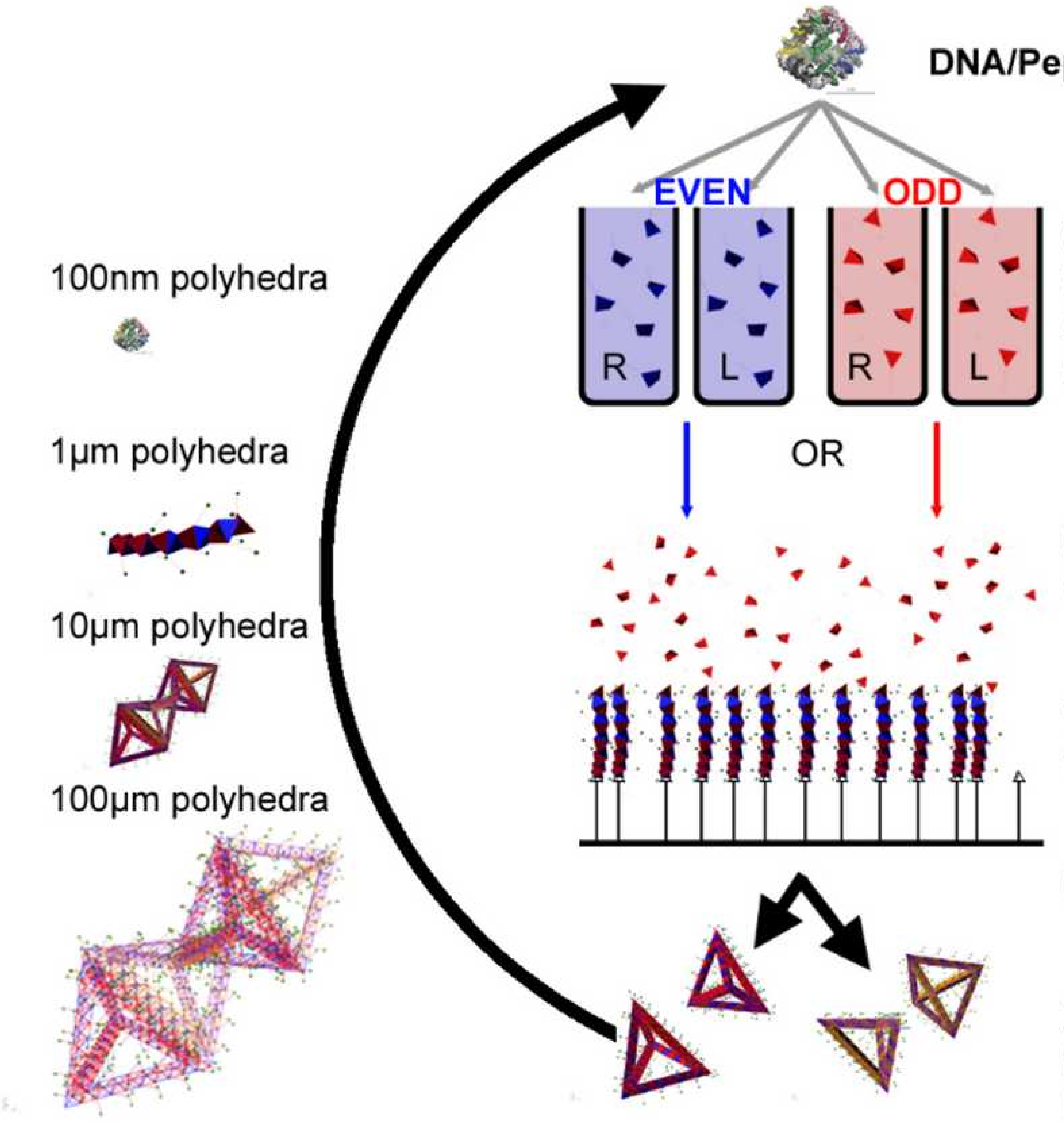


roll actuation with torque tube



high speed actuation of roll torque tube

Hierarchical Fabrication by Coded Folding



100nm polyhedra

1µm polyhedra

10µm polyhedra

100µm polyhedra

DNA/Peptide Synthesis

Stock of right and left turning polyhedra that stick only to polyhedra of opposite parity

Flood with next type, depending on parity

Washable Substrate with nano-wire posts

Rinse and Repeat

X10 Stock from Folded Nanostructures

doi:10.1038/nature11075

Complex shapes self-assembled from single-stranded DNA tiles

Bryan Wei[1,2], Mingjie Dai[2,3] & Peng Yin[1,2]

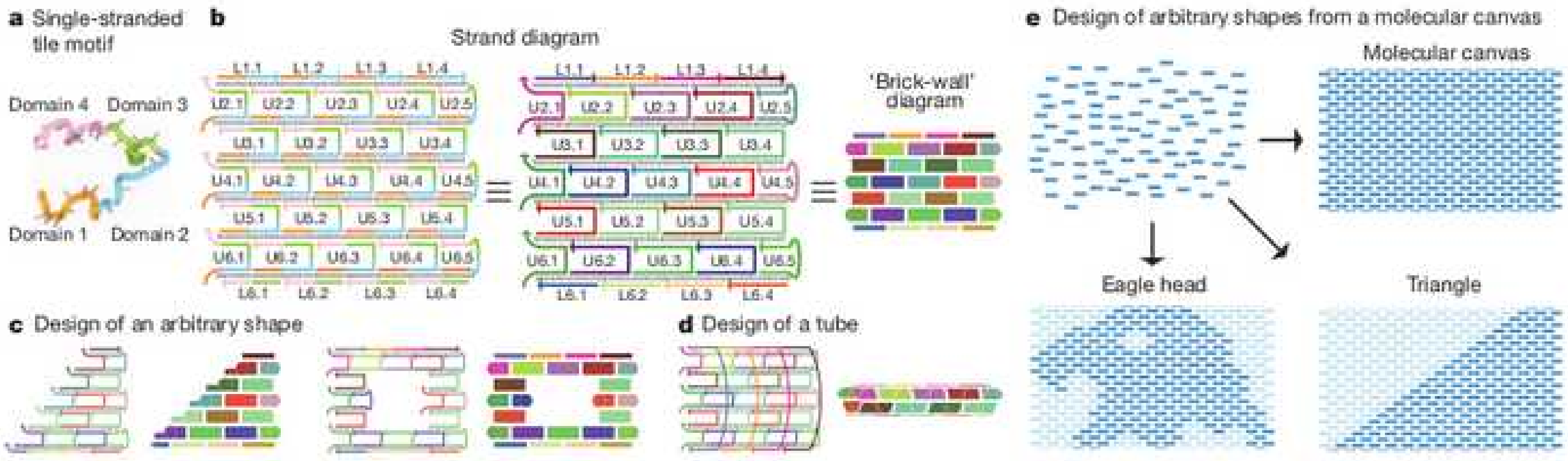


Figure 1 | Self-assembly of molecular shapes using single-stranded tiles. **a**, The canonical SST motif, adapted from ref. 12. **b**, Design of an SST rectangle structure. Left and middle: two different views of the same secondary structure diagram. Each standard (full) tile has 42 bases (labelled U), and each top and bottom boundary (half) tile has 21 bases (labelled L). Right: a simplified 'brick-wall' diagram. Standard tiles are depicted as thick rectangles, boundary tiles are depicted as thin rectangles and the unstructured single-stranded portions of the boundary tiles are depicted as rounded corners. Each strand has a unique sequence. Colours distinguish domains in the left panel and distinguish strands in the middle and right panels. **c**, Selecting an appropriate subset of SST species from the common pool in **b** makes it possible to design a desired target shape, for example a triangle (left) or a rectangular ring (right). **d**, Design of a tube with prescribed width and length. **e**, Arbitrary shapes can be designed by selecting an appropriate set of monomers from a pre-synthesized pool that corresponds to a molecular canvas (top right). To make a shape, the SST strands corresponding to its constituent pixels (dark blue) will be included in the strand mixture and the remainder (light blue) will be excluded.

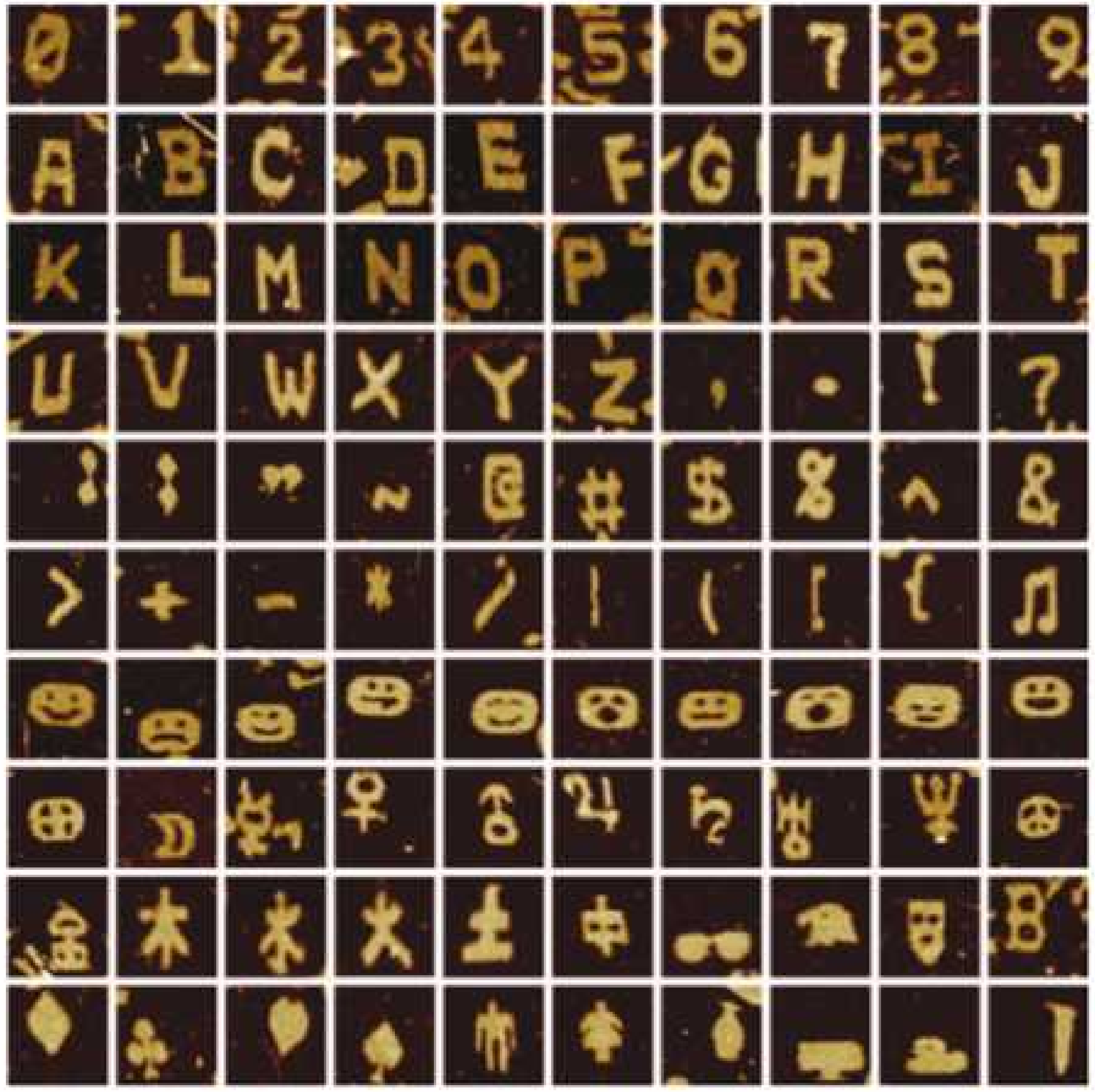
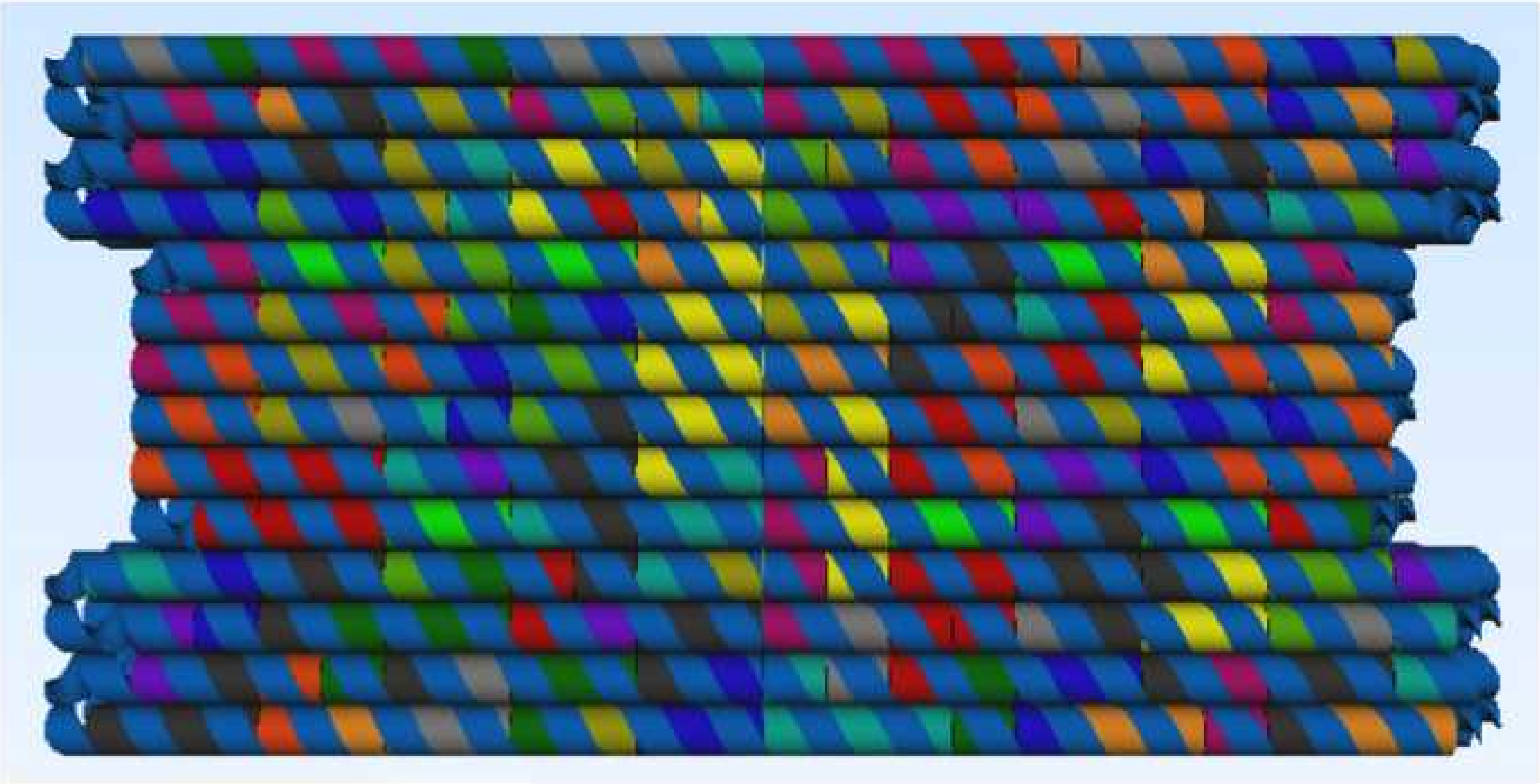
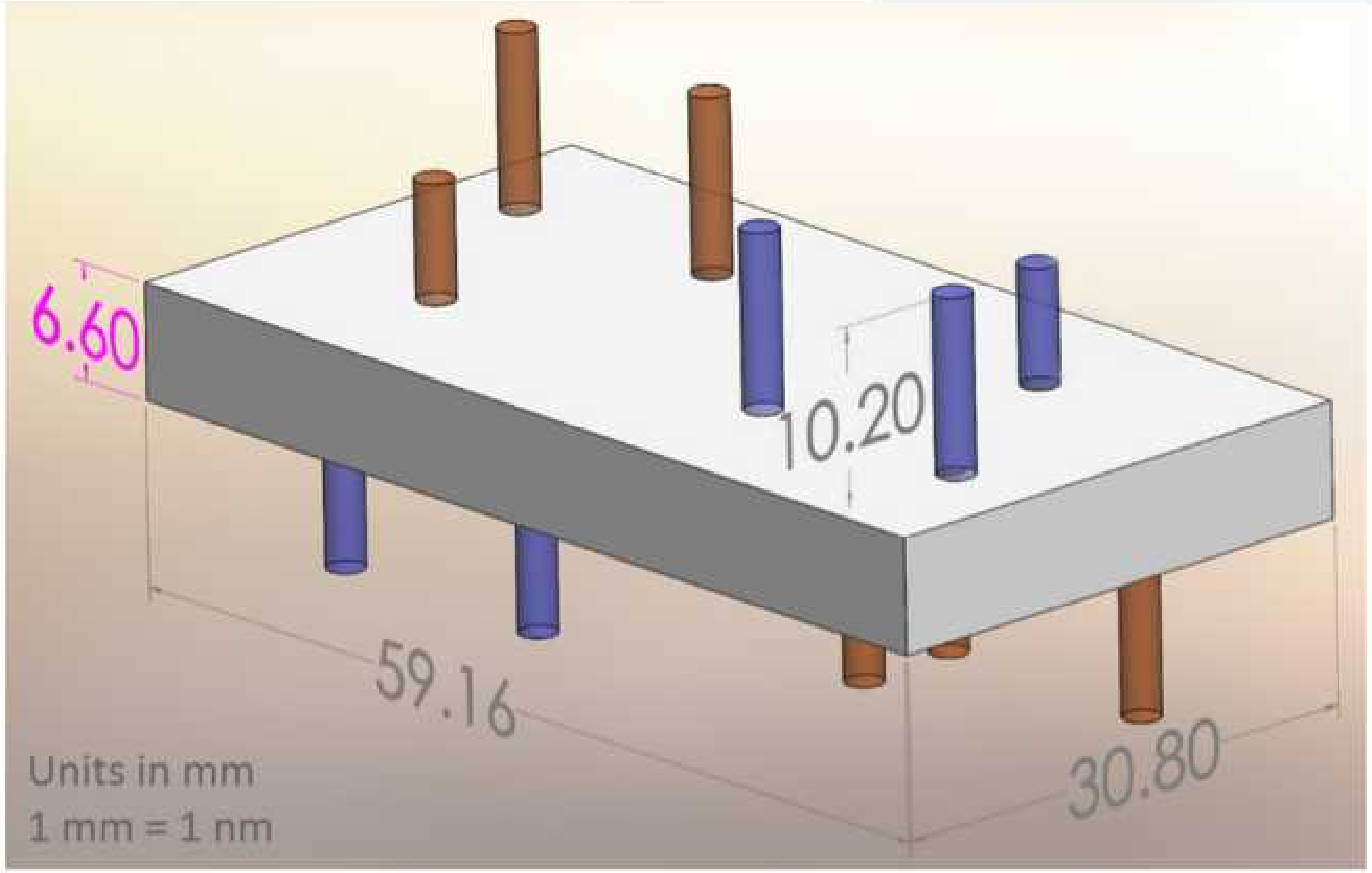


Figure 4 | Complex shapes designed using a molecular canvas. AFM images of 100 distinct shapes, including the 26 capital letters of the Latin alphabet, 10 Arabic numerals, 23 punctuation marks and other standard keyboard symbols, 10 emoticons, 9 astrological symbols, 6 Chinese characters and various miscellaneous symbols. Each image is 150 nm × 150 nm in size.

Bricks

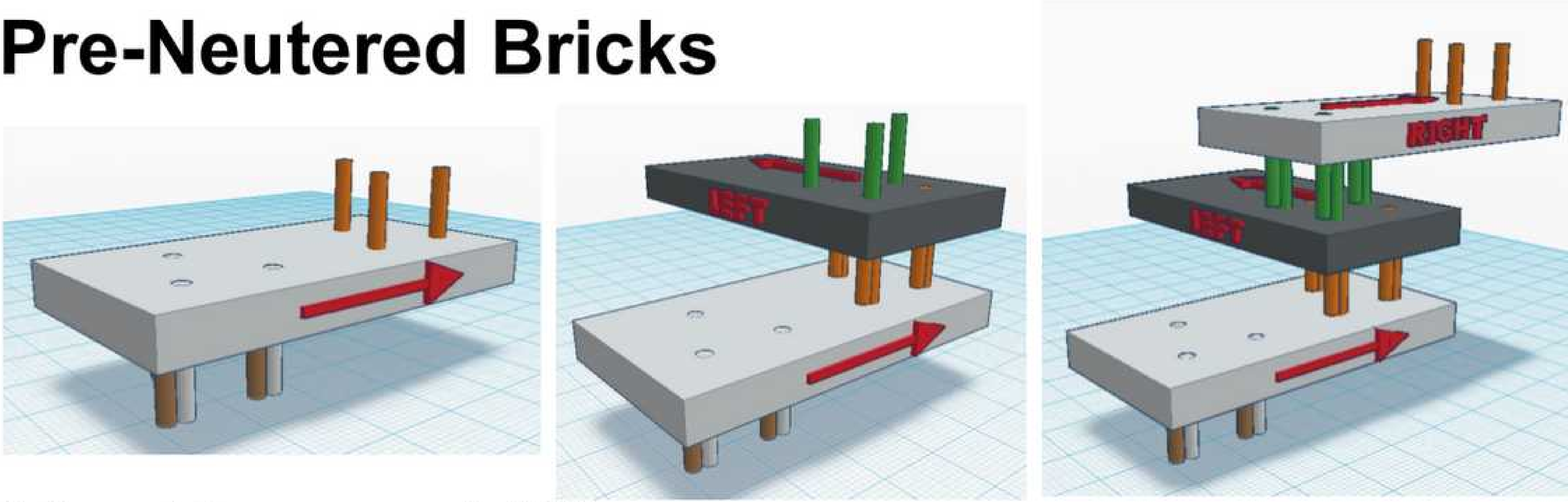




(Charles Fracchia)

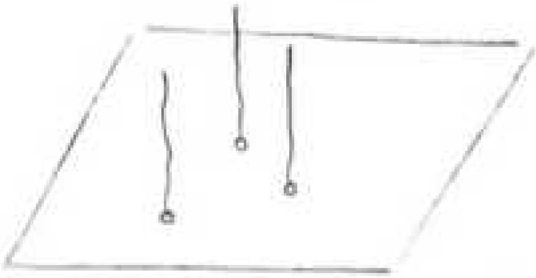
Assembly process

Pre-Neutered Bricks

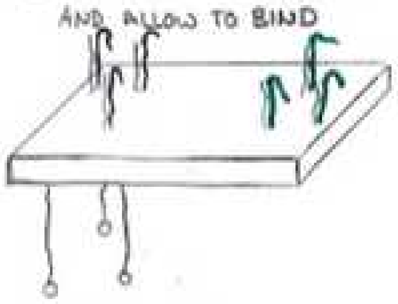


Live Reversability

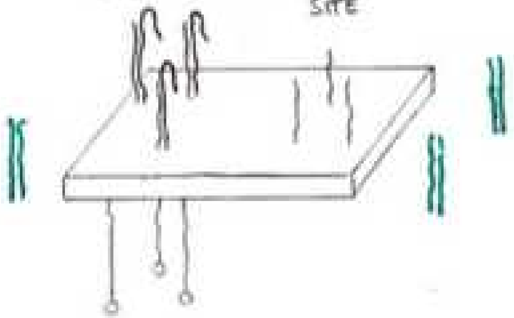
① ATTACH ANCHORING LINKERS TO FLOW CELL SURFACE

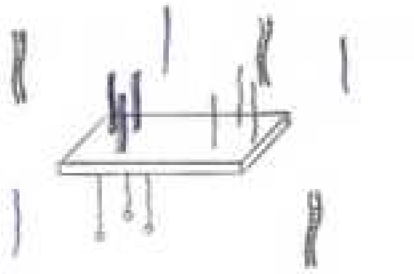


② WASH WITH FIRST BRICK AND ALLOW TO BIND



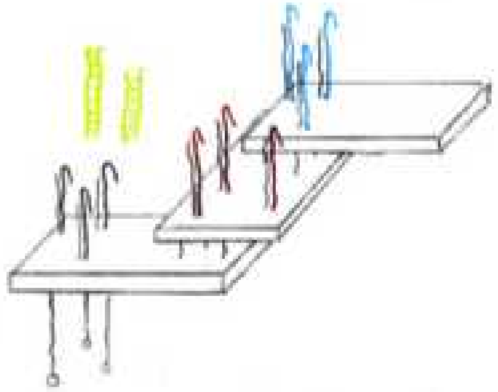
③ ADD DEPROTECTING OLIGOS FOR THE SPECIFIC SITE



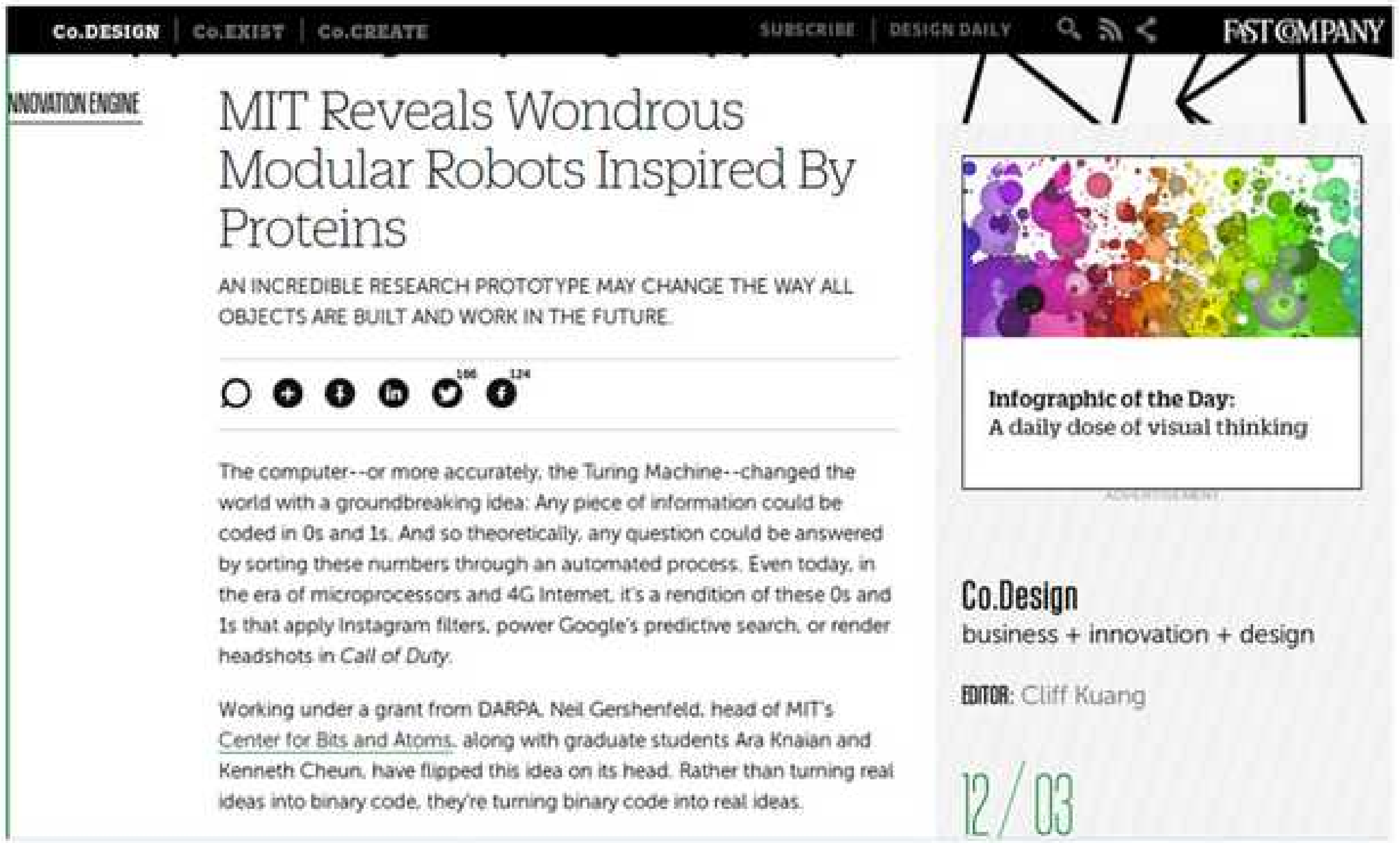


④ NEUTER THE UNUSED POSITIONS WITH OLIGOS THAT HAVE NO PEEL OFF OVERHANG

⑤ FLOW NEXT BRICK AND ALLOW LINKING



⑥ REPEAT STEPS 3,4 & 5 TO GROW GEOMETRY



MIT Reveals Wondrous Modular Robots Inspired By Proteins

AN INCREDIBLE RESEARCH PROTOTYPE MAY CHANGE THE WAY ALL OBJECTS ARE BUILT AND WORK IN THE FUTURE.

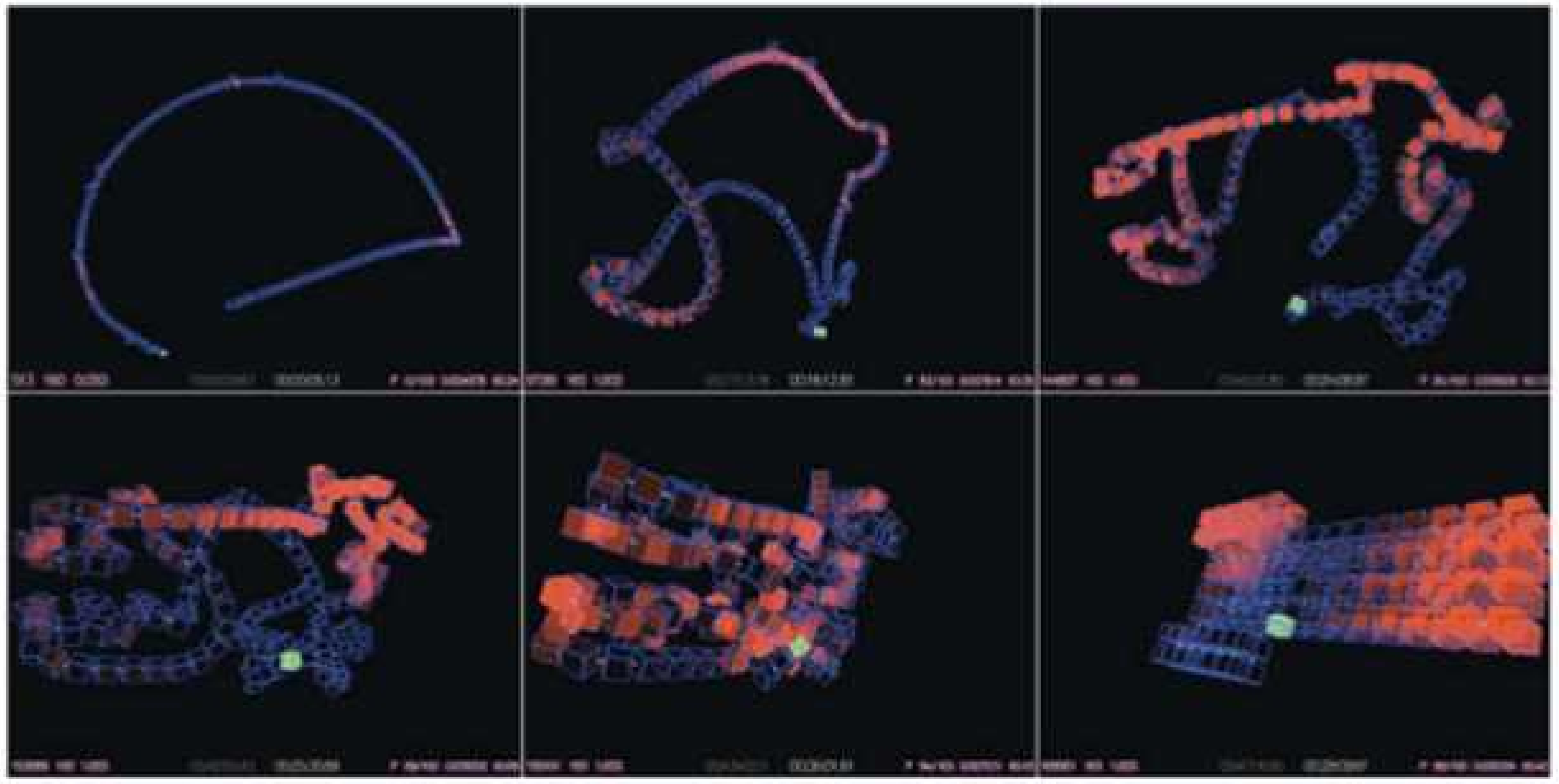
The computer--or more accurately, the Turing Machine--changed the world with a groundbreaking idea: Any piece of information could be coded in 0s and 1s. And so theoretically, any question could be answered by sorting these numbers through an automated process. Even today, in the era of microprocessors and 4G Internet, it's a rendition of these 0s and 1s that apply Instagram filters, power Google's predictive search, or render headshots in *Call of Duty*.

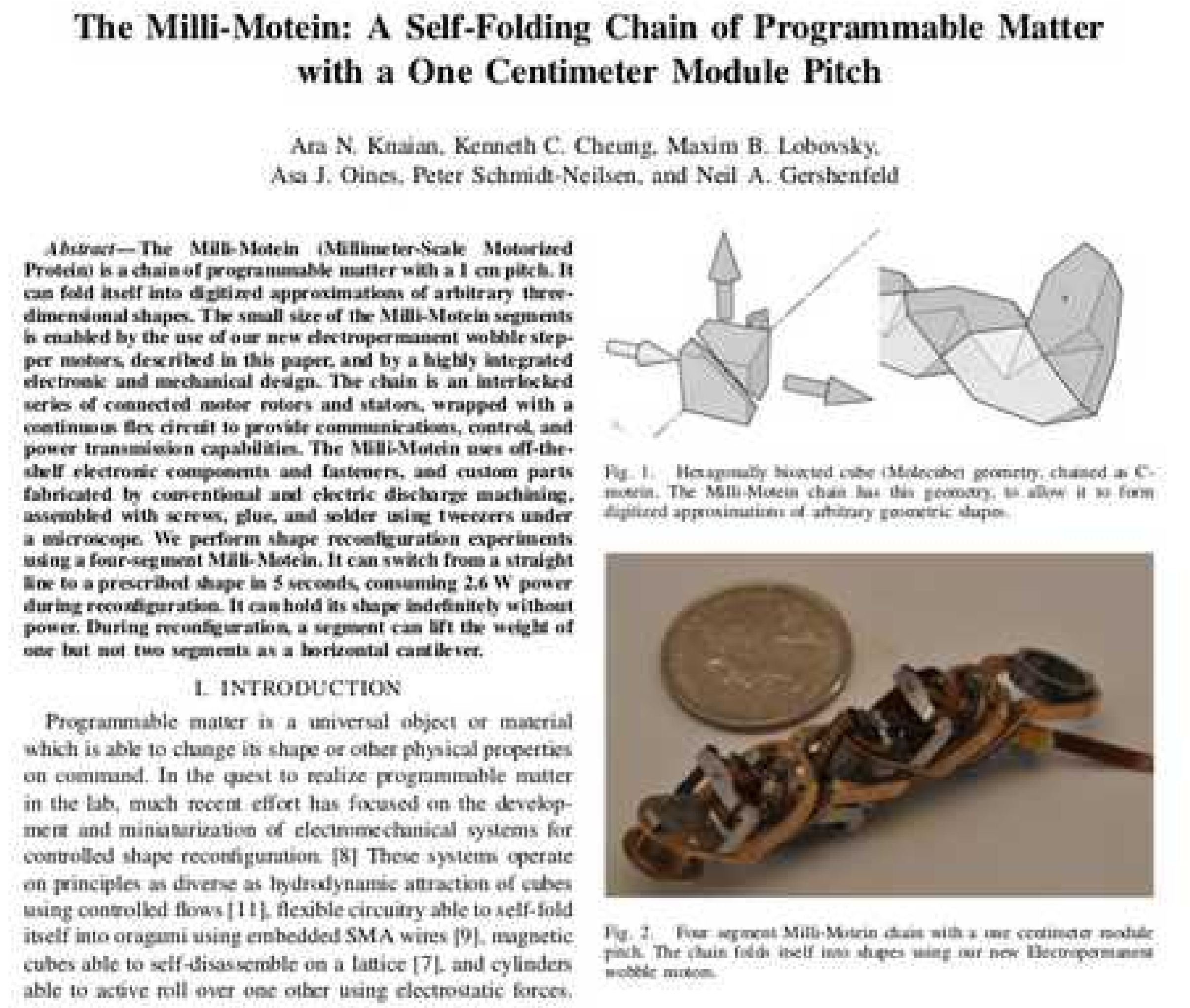
Working under a grant from DARPA, Neil Gershenfeld, head of MIT's Center for Bits and Atoms, along with graduate students Ara Knaian and Kenneth Cheun, have flipped this idea on its head. Rather than turning real ideas into binary code, they're turning binary code into real ideas.

Co.Design
business + innovation + design

EDITOR: Cliff Kuang

12/03





The Milli-Motein: A Self-Folding Chain of Programmable Matter with a One Centimeter Module Pitch

Ara N. Knaian, Kenneth C. Cheung, Maxim B. Lobovsky,
Asa J. Oines, Peter Schmidt-Neilsen, and Neil A. Gershenfeld

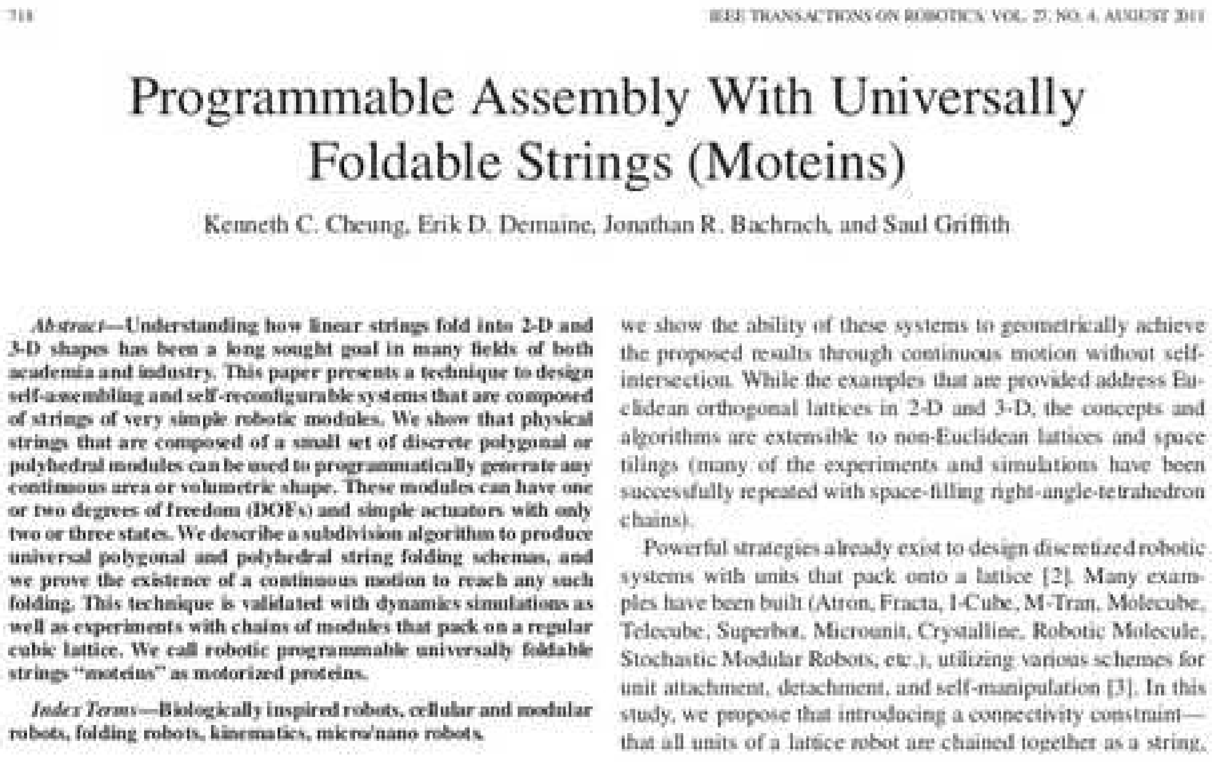
***Abstract*—The Milli-Motein (Millimeter-Scale Motorized Protein) is a chain of programmable matter with a 1 cm pitch. It can fold itself into digitized approximations of arbitrary three-dimensional shapes. The small size of the Milli-Motein segments is enabled by the use of our new electropermanent wobble stepper motors, described in this paper, and by a highly integrated electronic and mechanical design. The chain is an interlocked series of connected motor rotors and stators, wrapped with a continuous flex circuit to provide communications, control, and power transmission capabilities. The Milli-Motein uses off-the-shelf electronic components and fasteners, and custom parts fabricated by conventional and electric discharge machining, assembled with screws, glue, and solder using tweezers under a microscope. We perform shape reconfiguration experiments using a four-segment Milli-Motein. It can switch from a straight line to a prescribed shape in 5 seconds, consuming 2.6 W power during reconfiguration. It can hold its shape indefinitely without power. During reconfiguration, a segment can lift the weight of one but not two segments as a horizontal cantilever.**

I. INTRODUCTION

Programmable matter is a universal object or material which is able to change its shape or other physical properties on command. In the quest to realize programmable matter in the lab, much recent effort has focused on the development and miniaturization of electromechanical systems for controlled shape reconfiguration. [8] These systems operate on principles as diverse as hydrodynamic attraction of cubes using controlled flows [11], flexible circuitry able to self-fold itself into oragami using embedded SMA wires [9], magnetic cubes able to self-disassemble on a lattice [7], and cylinders able to active roll over one other using electrostatic forces.

Fig. 1. Hexagonally bisected cube (Molecube) geometry, chained as C-motein. The Milli-Motein chain has this geometry, to allow it to form digitized approximations of arbitrary geometric shapes.

Fig. 2. Four segment Milli-Motein chain with a one centimeter module pitch. The chain folds itself into shapes using our new Electropermanent wobble motors.



Programmable Assembly With Universally Foldable Strings (Moteins)

Kenneth C. Cheung, Erik D. Demaine, Jonathan R. Bachrach, and Saul Griffith

***Abstract*—Understanding how linear strings fold into 2-D and 3-D shapes has been a long sought goal in many fields of both academia and industry. This paper presents a technique to design self-assembling and self-reconfigurable systems that are composed of strings of very simple robotic modules. We show that physical strings that are composed of a small set of discrete polygonal or polyhedral modules can be used to programmatically generate any continuous area or volumetric shape. These modules can have one or two degrees of freedom (DOFs) and simple actuators with only two or three states. We describe a subdivision algorithm to produce universal polygonal and polyhedral string folding schemas, and we prove the existence of a continuous motion to reach any such folding. This technique is validated with dynamics simulations as well as experiments with chains of modules that pack on a regular cubic lattice. We call robotic programmable universally foldable strings "moteins" as motorized proteins.**

***Index Terms*—Biologically inspired robots, cellular and modular robots, folding robots, kinematics, micro/nano robots.**

we show the ability of these systems to geometrically achieve the proposed results through continuous motion without self-intersection. While the examples that are provided address Euclidean orthogonal lattices in 2-D and 3-D, the concepts and algorithms are extensible to non-Euclidean lattices and space tilings (many of the experiments and simulations have been successfully repeated with space-filling right-angle-tetrahedron chains).

Powerful strategies already exist to design discretized robotic systems with units that pack onto a lattice [2]. Many examples have been built (Atron, Fracta, I-Cube, M-Tran, Molecube, Telecube, Superbot, Microunit, Crystalline, Robotic Molecule, Stochastic Modular Robots, etc.), utilizing various schemes for unit attachment, detachment, and self-manipulation [3]. In this study, we propose that introducing a connectivity constraint—that all units of a lattice robot are chained together as a string,

THE CENTER FOR BITS AND ATOMS
Massachusetts Institute of Technology

The Science of Digital Fabrication

March 7, 2013
MIT

Executive Office of the President of the United States
Office of Science and Technology Policy

8:00-9:00 *Registration* (E14-638)

9:00-10:30 *Briefings: Materials and Mechanisms* (E14-674)

Introduction: *Neil Gershenfeld*
History: *Saul Griffith*
Fabricational Complexity: *Joe Jacobson*
Digital Materials: *Kenny Cheung*
Self-Assembly: *Ned Seeman*
Nano-assembly: *Peng Yin*
Micro-assembly: *Will Langford*
Meso-assembly: *Hod Lipson*
Macro-assembly: *Skylar Tibbits*
Mega-assembly: *Larry Sass*

10:30-11:00 *Break* (E14-638)

11:00-12:30 *Briefings: Processes and Workflows* (E14-674)

Simulation and Optimization: *Wojciech Matusik*
3D Scanning: *Philip Withers*
Design Representations and Interfaces: *Matthew Keeter*
Path Planning: *Sanjay Sarma*
Motion Control: *Nadya Peek*
Printing: *Jennifer Lewis*
Folding: *Erik Demaine*
Programmable Matter: *Daniela Rus*
Little Data: *George Church*
Self-Reproducing Systems: *John Glass*

12:30-2:00 *Lunch: Demonstrations* (E14-638,648)

2:00-3:30 *Briefings: Policy and Programs* (E14-674)

OSTP: *Philip Rubin* (video)
NIST: *John Slotwinski*
DARPA: *Paul Eremenko*
NSF: *Richard Voyles*
NASA: *LaNetra Tate*
DOE: *Kelly Visconti*
DHS: *Jose Vazquez*
Make: *Dale Dougherty*
MacArthur Foundation: *Connie Yowell*
Barcelona: *Vicente Guallart*
Rep. *Bill Foster*

3:30-4:15 *Working Groups* (E14-638,648)

Policy, Programs: *Tom Kalil* (video)
Standards, Formats: *Hod Lipson*
Facilities, Infrastructure: *Jim Newton*
Communication, Publication: *Joe Jacobson*
Education, Outreach: *Sherry Lassiter*

4:30-5:00 *Discussion* (E14-674)

5:00-6:30 *Reception: Exhibition* (E14-638,648)

6:30-8:00 *Goldstein Lecture* (10-250)

The Design of Robotic Fabricated Architecture: *Matthias Kohler*

FOREIGN
AFFAIRS

NOVEMBER/DECEMBER 2012

How to Make Almost Anything

The Digital Fabrication Revolution

Neil Gershenfeld

Volume 91 • Number 6