Curricular Innovation in Engineering Education:

- ✏ in the Science Core
- ✏ in Materials Science

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Outline of today's talk

- what is engineering?
- the future
- undergraduate education
  - MIT science core
  - MIT Materials Science S.B.

What is an engineer?

What does the *Oxford English Dictionary* say?

1. One who contrives, designs, or invents; an author, designer

2. a. A constructor of military engines (obs.)

   b. One who designs and constructs military works for attack or defense

"A tour ful strong, That queyntyly engynours made."

- c. 1325 Coer de L.

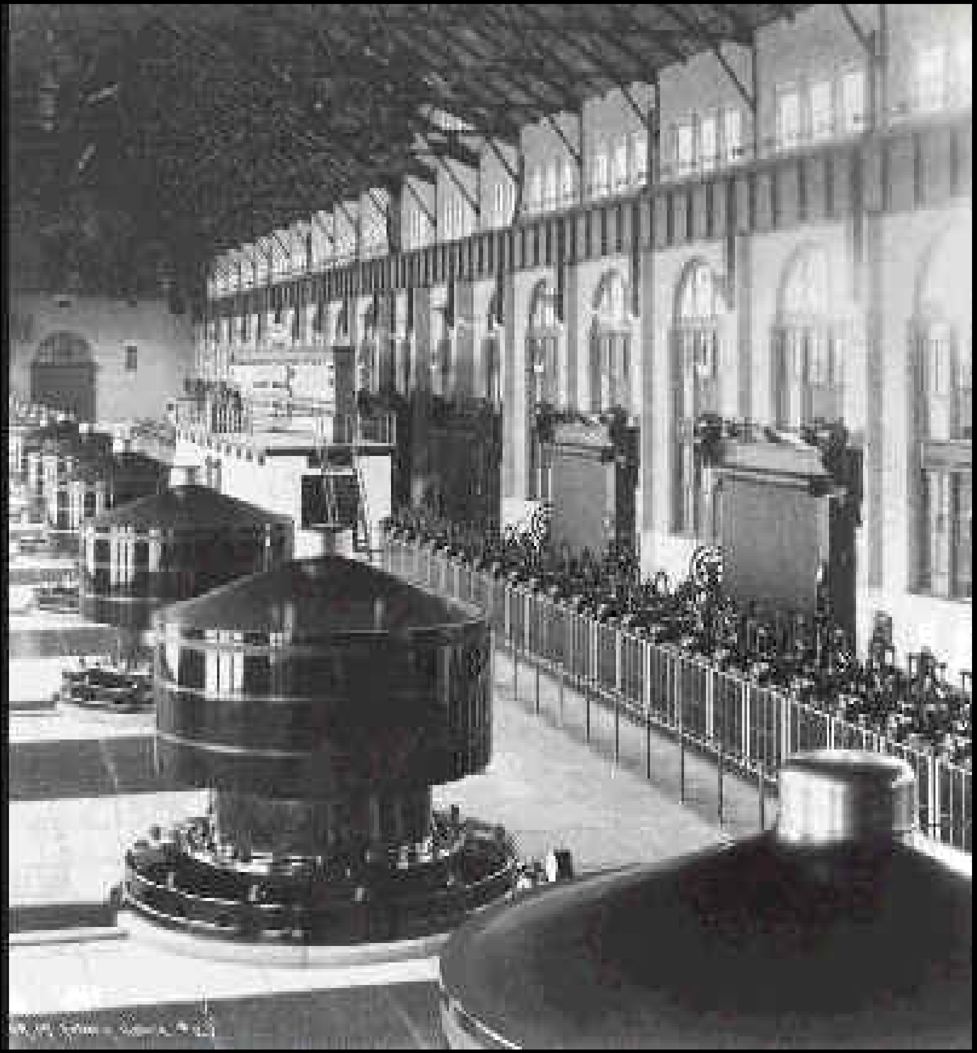
engineer

"engineer" and "ingenious"

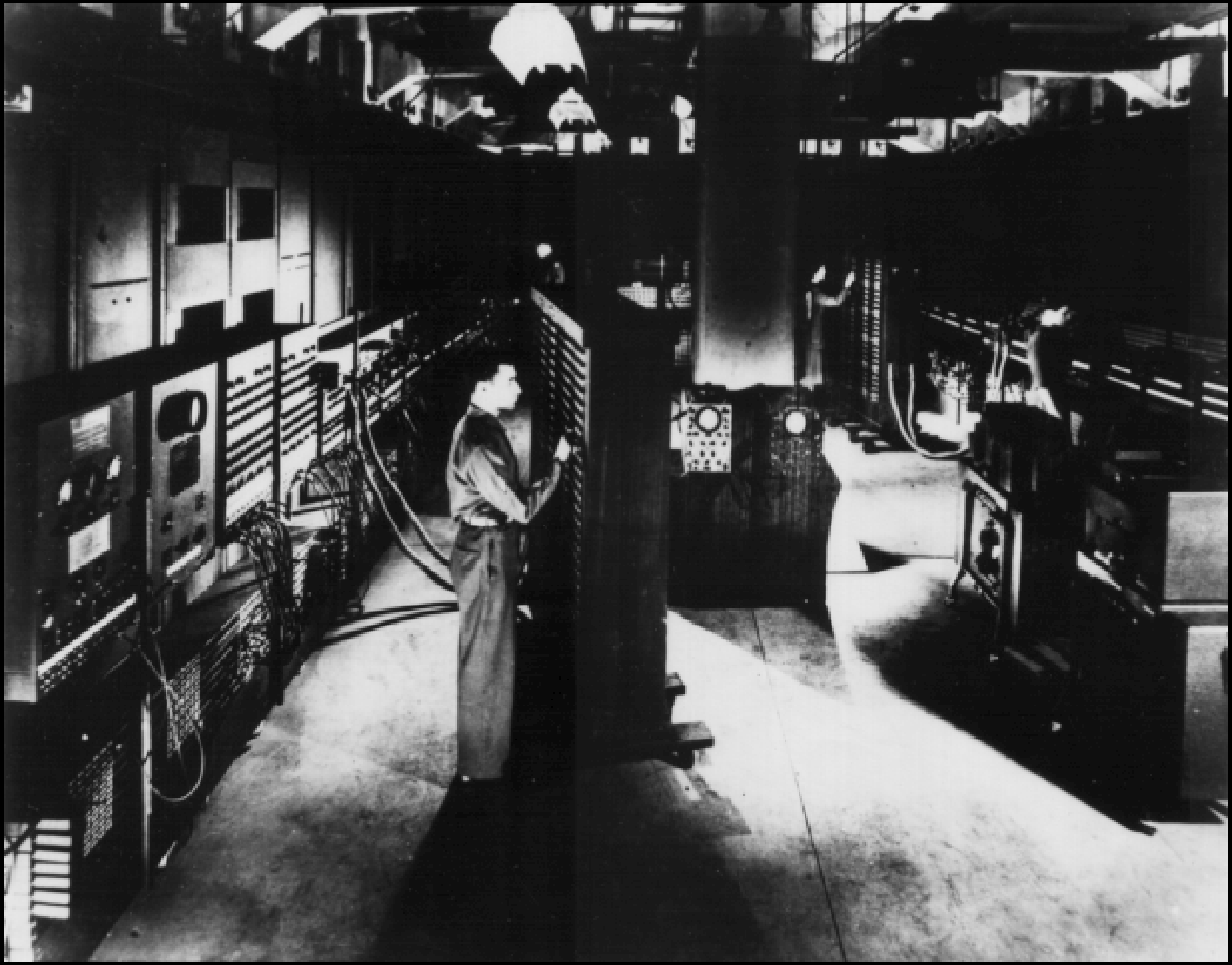
have the same root

Civil engineering

Electrical engineering



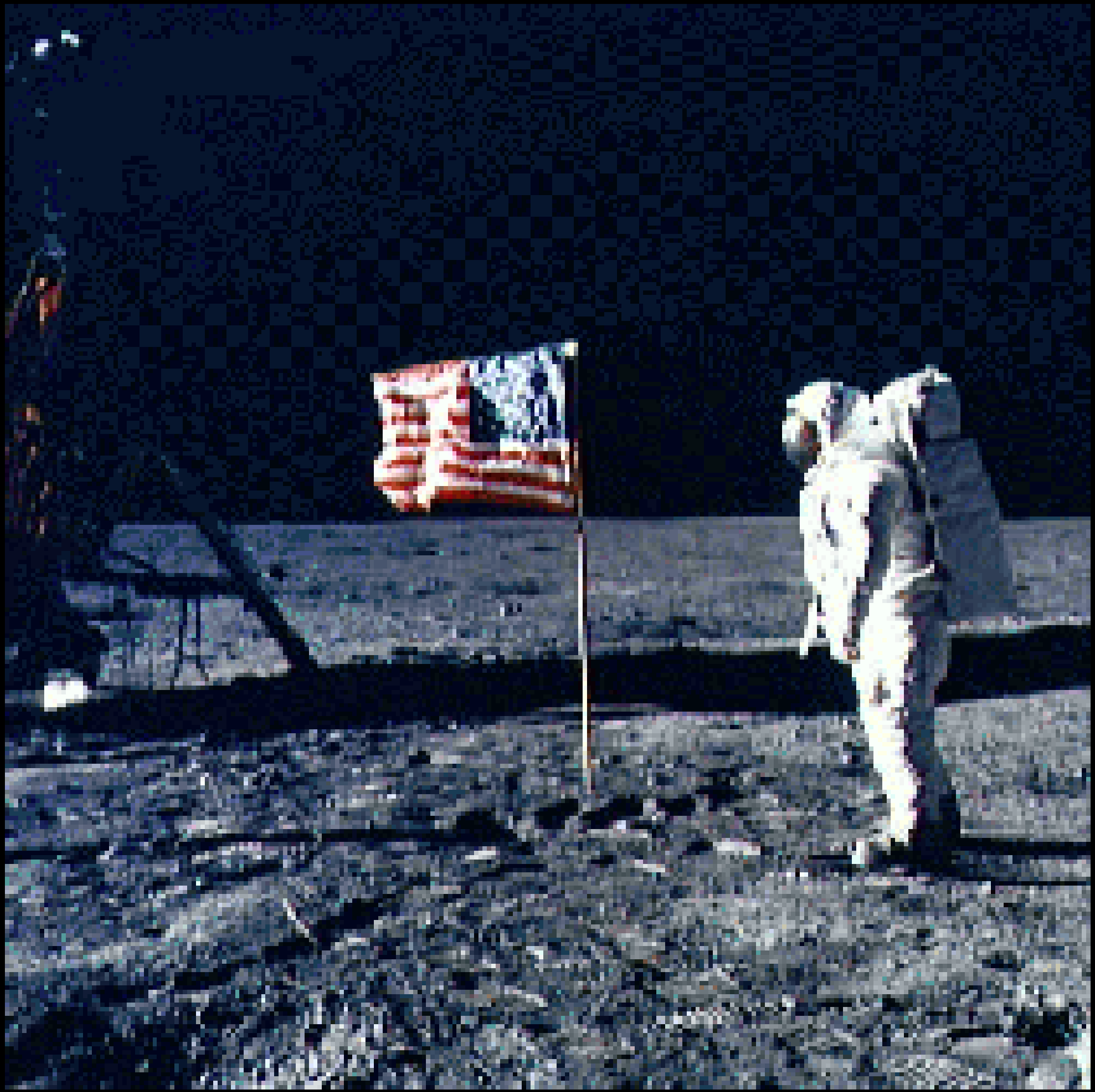
Computer science



Mechanical engineering

Metallurgical engineering

Modern engineering systems



Modern engineering systems

Modern engineering systems

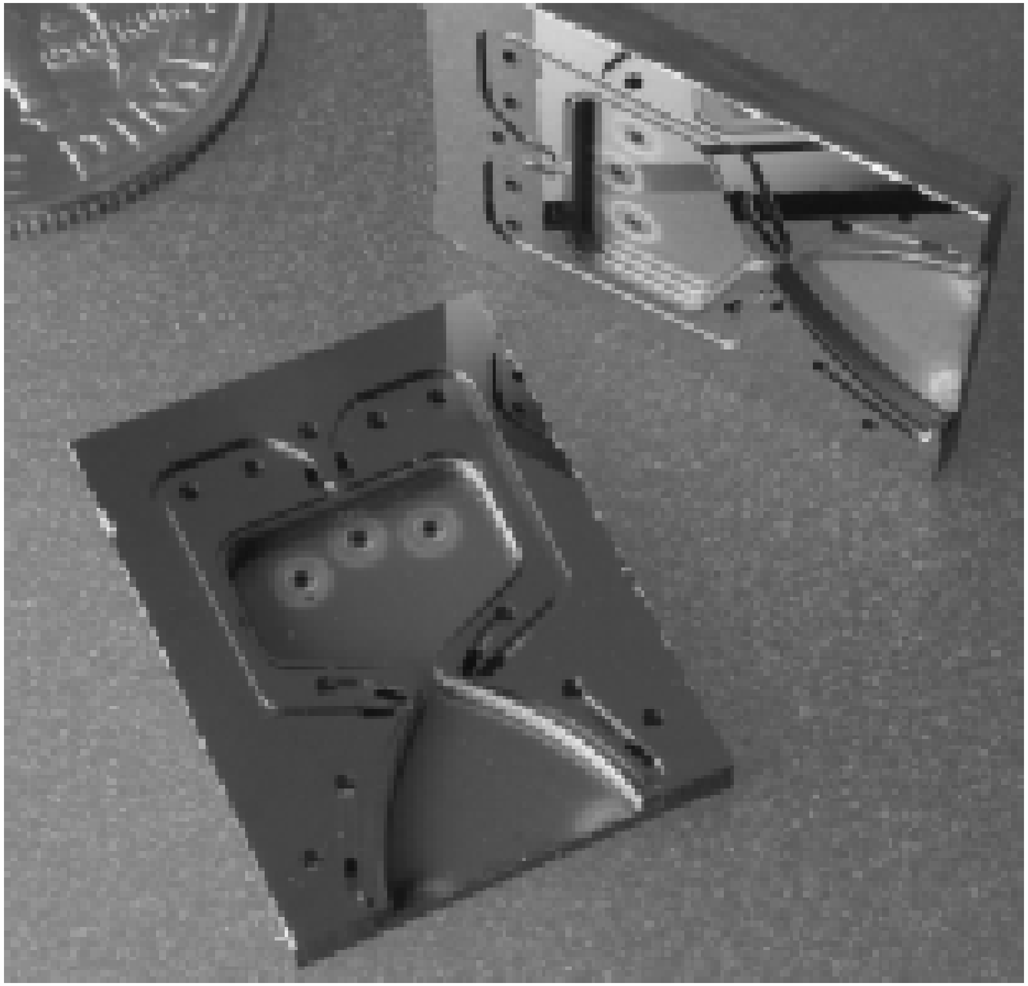
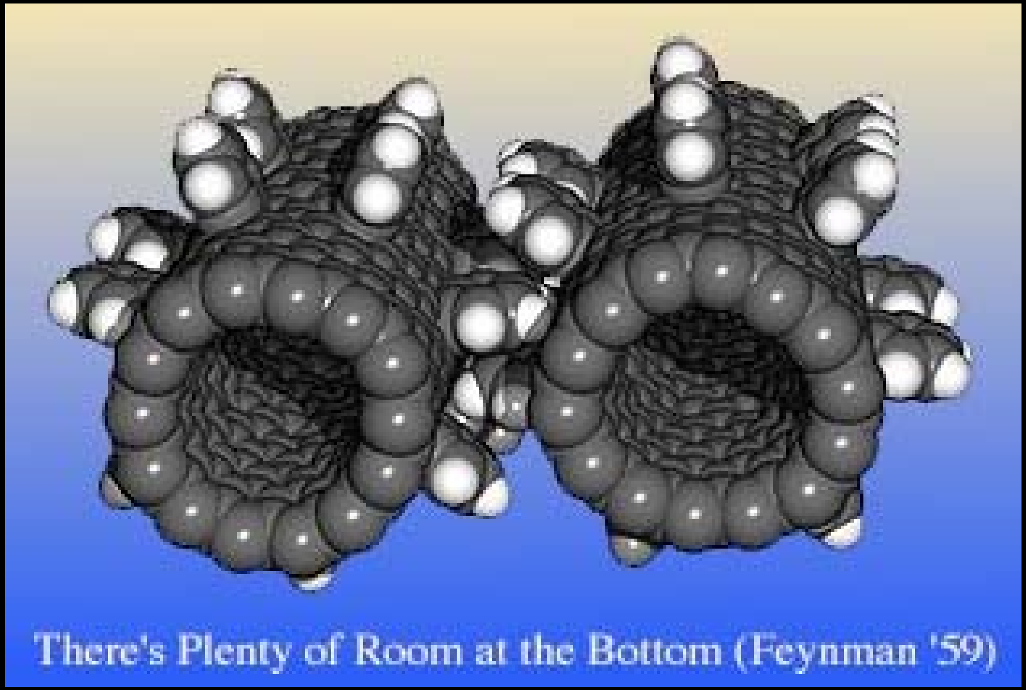
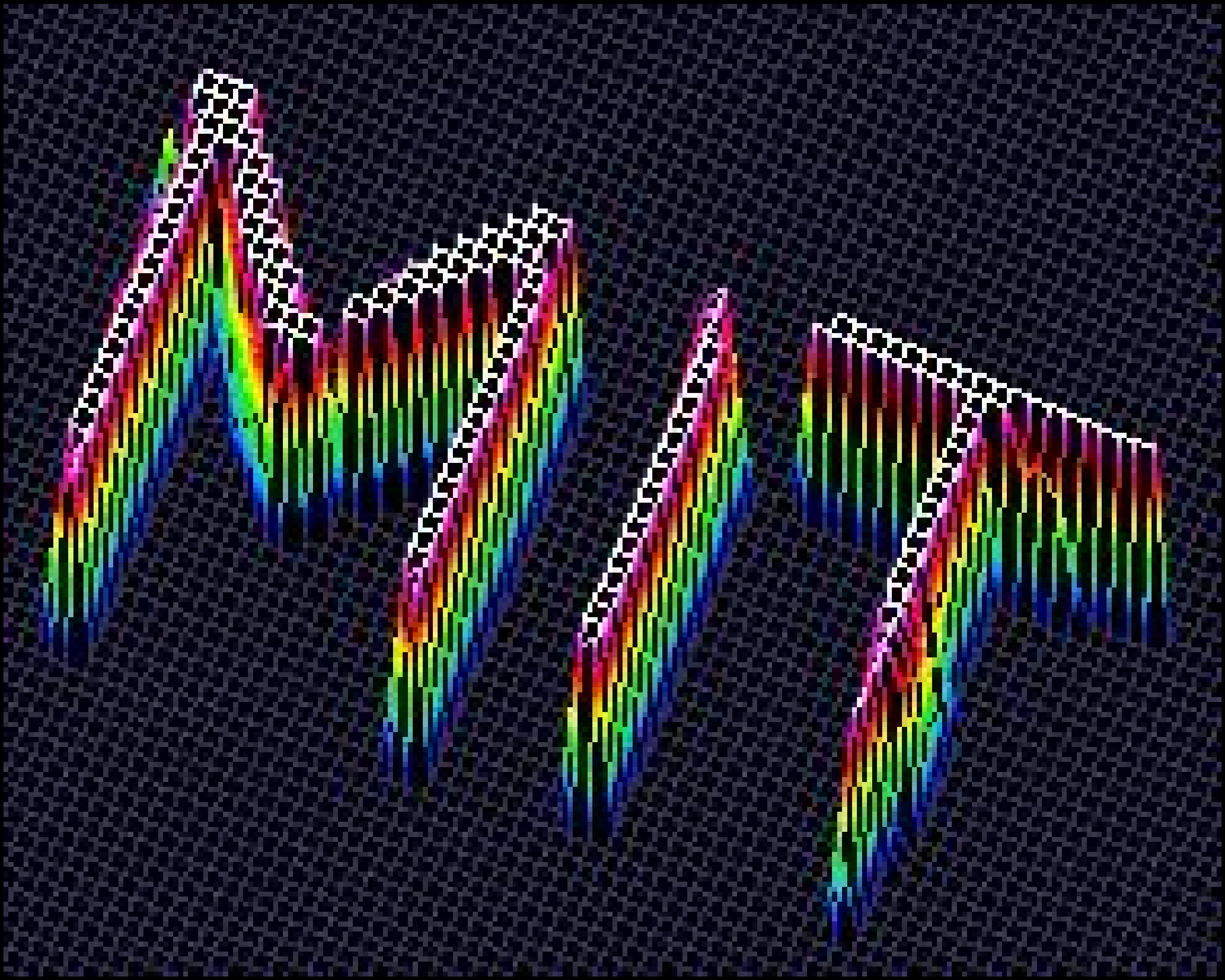


Fig. 50: A six wafer microrocket engine

Modern engineering systems

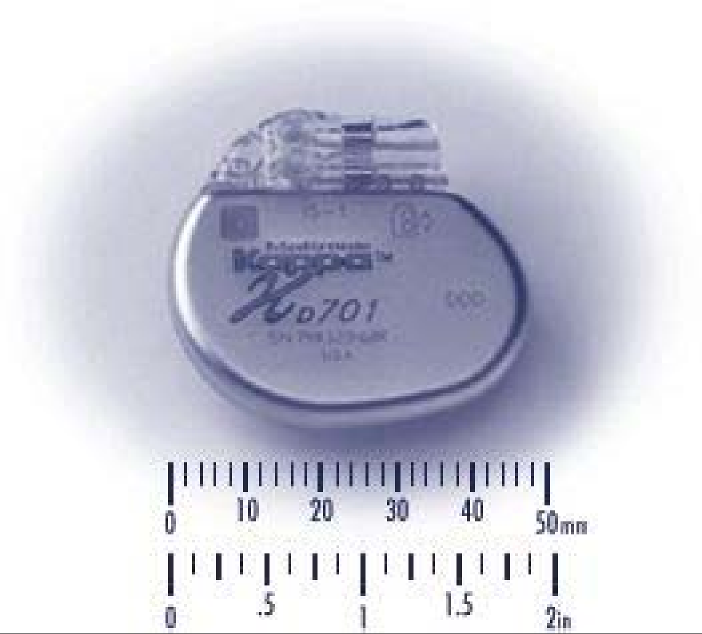


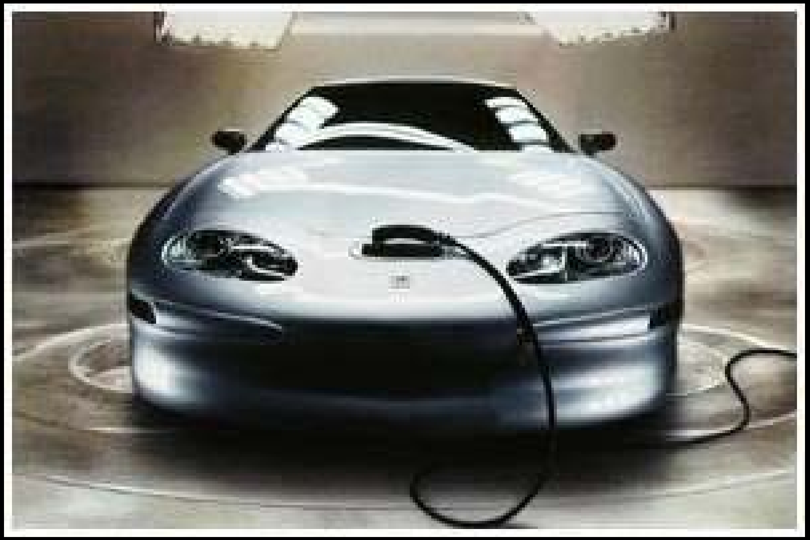
Modern engineering systems



Modern engineering systems

Modern engineering systems





An important distinction

A scientist discovers that which exists.

An engineer creates that which never was.

- Theodore von Kármán

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- what is engineering?
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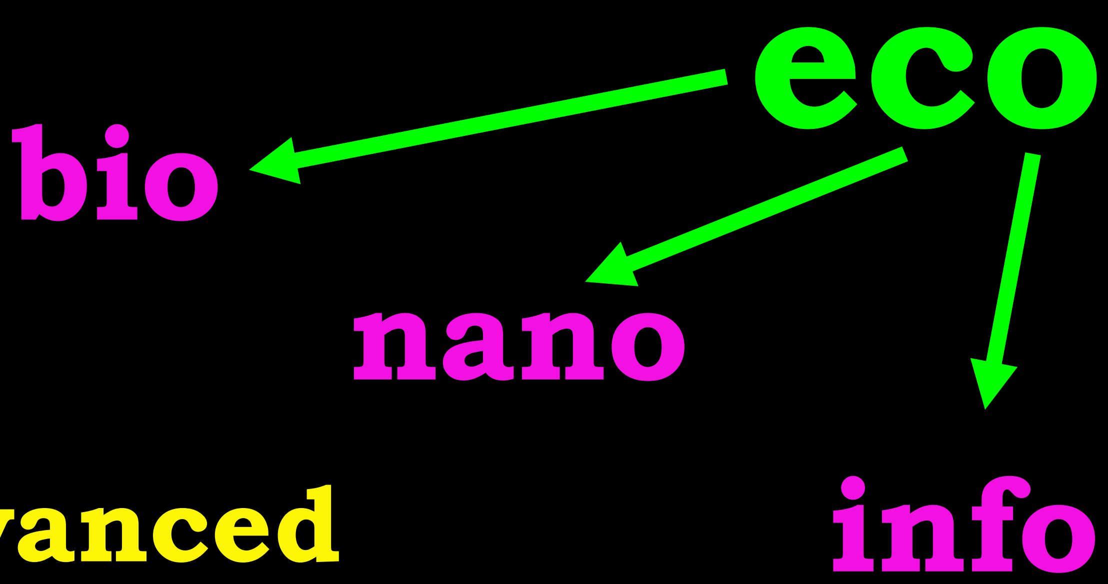
the future

Prediction is very difficult, especially about the future.

- Niels Bohr

futureworld: the 3 big Os



advanced materials

imagine the future

EMERGING TECHNOLOGIES THAT WILL CHANGE THE WORLD

10

THE TECHNOLOGY REVIEW TEN

What if you had a crystal ball that foretold the future of technology? Imagine, for example, if you had known in 1990 just how big the Internet was going to be 10 years hence. Sorry, that crystal ball doesn't exist. But in this special issue of *Technology Review*, we offer you the next best thing: the educated predictions of our editors (made in consultation with some of technology's top experts). We have chosen 10 emerging areas of technology that will soon have a profound impact on the economy and on how we live and work. These advances span information technology, biotechnology and nanotechnology—the core of *TR* coverage in every issue. All of these areas merit special attention in the decade to come. In each area we've chosen to highlight one innovator who exemplifies the potential and promise of the field. Keep this issue around and see how well our predictions hold up—even without the aid of that crystal ball. —*The Editors*

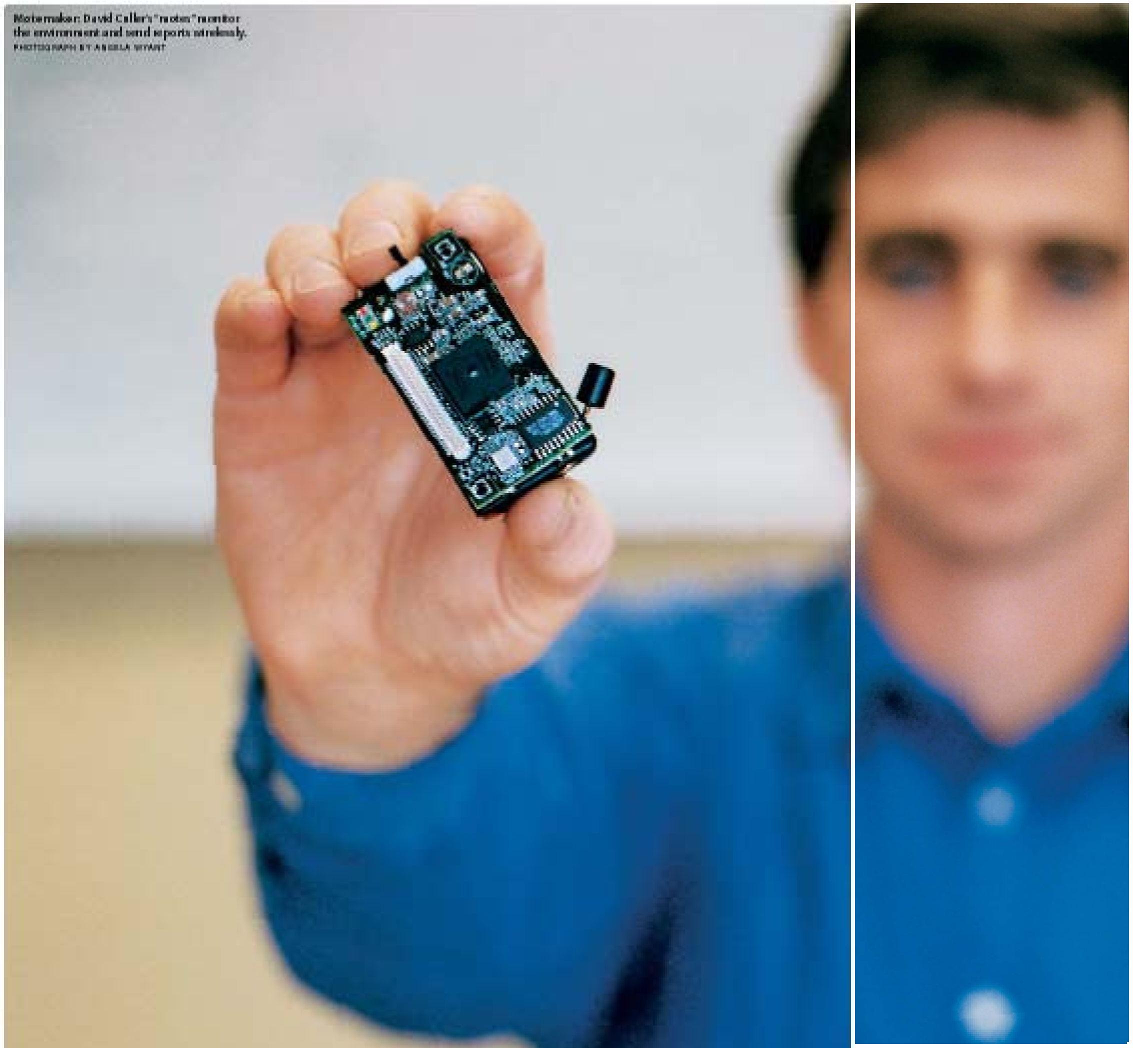
TECHNOLOGY

FEBRUARY 2003

In labs around the world, researchers are busy creating technologies that will change the way we conduct business and live our lives. These are not the latest crop of gadgets and gizmos: they are completely new technologies that could soon transform computing, medicine, manufacturing, transportation, and our energy infrastructure. Nurturing the people and the culture needed to make the birth of such technological ideas possible is a messy endeavor, as MIT Media Lab cofounder Nicholas Negroponte explains on page 34. But in this special issue, *Technology Review*'s editors have identified 10 emerging technologies that we predict will have a tremendous influence in the near future. For each, we've chosen a researcher or research team whose work and vision is driving the field. The profiles, which begin on page 36, offer a sneak preview of the technology world in the years and decades to come.

10 EMERGING TECHNOLOGIES THAT WILL CHANGE THE WORLD

imagine the future



Motemaker: David Culler's "motes" monitor the environment and send reports wirelessly.
PHOTOGRAPH BY ANGELA WYANT

DAVID CULLER

Wireless Sensor Networks

Great Duck Island, a 90-hectare expanse of rock and grass off the coast of Maine, is home to one of the world's largest breeding colonies of Leach's storm petrels—and to one of the world's most advanced experiments in wireless networking. Last summer, researchers bugged dozens of the petrels' nesting burrows with small monitoring devices called motes. Each is about the size of its power source—a pair of AA batteries—and is equipped with a processor, a tiny amount of computer memory, and sensors that monitor light, humidity, pressure, and heat. There's also a radio transceiver just powerful enough to broadcast snippets of data to nearby motes and pass on information received from other neighbors, bucket brigade–style.

This is more than the latest in avian intelligence gathering. The motes preview a future pervaded by networks of wireless battery-powered sensors that monitor our environment, our machines, and even us. It's a future that David Culler, a computer scientist at the University of California, Berkeley, has been working toward for the last four years. "It's one of the big opportunities" in information technology, says Culler. "Low-power wireless sensor networks are spearheading what the future of computing is going to look like."

Culler is on partial leave from Berkeley to direct an Intel "lablet" that is perfecting the motes, as well as the hardware and software systems needed to clear the way for wireless networks made up of thousands or even millions of sensors. These networks will observe just about everything, including traffic, weather, seismic activity, the movements of troops on battlefields, and the stresses on buildings and bridges—all on a far finer scale than has been possible before.

Because such networks will be too distributed to have the sensors hard-wired into the electrical or communications grids, the lablet's first challenge was to make its prototype motes communicate wirelessly with minimal battery power. "The devices have to organize themselves in a network by listening to one another and figuring out who can they hear...but it costs power to even listen," says Culler. That meant finding a way to leave the motes' radios off most of the time and still allow data to hop through the network, mote by mote, in much the same way that data on the Internet are broken into packets and routed from node to node.

Until Culler's group attacked the problem, wireless networking had lacked an equivalent to the data-handling protocols that make the Internet work. The lablet's solution: TinyOS, a compact operating system only a few kilobytes in size, that handles such administrative tasks as encoding data packets for relay and turning on radios only when they're needed. The motes that run TinyOS should cost a few dollars apiece when mass produced and are being field-tested in several locations from Maine to California, where Berkeley seismologists are using them to monitor earthquakes.

Anyone is free to download and tinker with TinyOS, so researchers outside of Berkeley and Intel can test wireless sensor networks in a range of environments without having to reinvent the underlying technology. Culler's motes have been "a tremendously enabling platform," says Deborah Estrin, director of the Center for Embedded Networked Sensing at the University of California, Los Angeles. Estrin is rigging a nature reserve in the San Jacinto mountains with a dense array of wireless microclimate and imaging sensors.

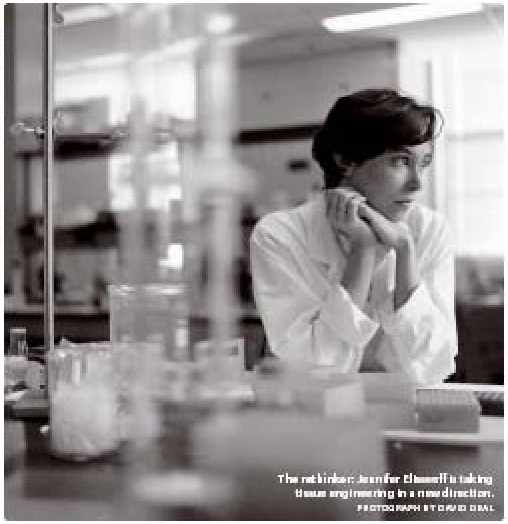
Others are trying to make motes even smaller. A group led by Berkeley computer scientist Kristofer Pister is aiming for one cubic millimeter—the size of a few dust mites. At that scale, wireless sensors could permeate highway surfaces, building materials, fabrics, and perhaps even our bodies. The resulting data bonanza could vastly increase our understanding of our physical environment—and help us protect our own nests. —*Wade Roush*

10 EMERGING TECHNOLOGIES

OTHERS IN WIRELESS SENSOR NETWORKS

RESEARCHER	PROJECT
Gaetano Borriello U. Washington; Intel	Small embedded computers and communications protocols
Deborah Estrin U. California, Los Angeles	Networking, middleware, data handling, and hardware for distributed sensors and actuators
Michael Horton Crossbow Technology	Manufacture of sensors and motes
Kristofer Pister U. California, Berkeley	Millimeter-size sensing and communication devices

imagine the future



The rethinker: Jennifer Elisseeff is taking tissue engineering in a new direction.
PHOTOGRAPH BY DAVID DEAL

JENNIFER ELISSEEFF

Injectable Tissue Engineering

Every year, more than 700,000 patients in the United States undergo joint replacement surgery. The procedure—in which a knee or a hip is replaced with an artificial implant—is highly invasive, and many patients delay the surgery for as long as they can. Jennifer Elisseeff, a biomedical engineer at Johns Hopkins University, hopes to change that with a treatment that does away with surgery entirely: injectable tissue engineering. She and her colleagues have developed a way to inject joints with specially designed mixtures of polymers, cells, and growth stimulators that solidify and form healthy tissue. "We're not just trying to improve the current therapy," says Elisseeff. "We're really trying to change it completely."

Elisseeff is part of a growing movement that is pushing the bounds of tissue engineering—a field researchers have long hoped would produce lab-grown alternatives to transplanted organs and tissues. For the last three decades, researchers have focused on growing new tissues on polymer scaffolds in the lab. While this approach has had success producing small amounts of cartilage and skin, researchers have had difficulty keeping cells alive on larger scaffolds. And even if those problems could be worked out, surgeons would still have to implant the lab-grown tissues. Now, Elisseeff, as well as other academic and industry researchers, are turning to injectable systems that are less invasive and far cheaper. Many of the tissue-engineering applications to reach the market first could be delivered by syringe rather than implants, and Elisseeff is pushing to make this happen as soon as possible.

Elisseeff and her colleagues have used an injectable system to grow cartilage in mice. The researchers added cartilage cells to a light-sensitive liquid polymer and injected it under the skin on the backs of mice. They then shone ultraviolet light through the skin, causing the polymer to harden and encapsulate the cells. Over time, the cells multiplied and developed into cartilage. To test the feasibility of the technique for minimally invasive surgery, the researchers injected the liquid into the knee joints of cadavers. The surgeons used a fiber-optic tube to view the hardening process on a television monitor. "This has huge implications," says James Wenz, an orthopedic surgeon at Johns Hopkins who is collaborating with Elisseeff.

While most research on injectable systems has focused on cartilage and bone, observers say this technology could be extended to tissues such as those of the liver and heart. The method could be used to replace diseased portions of an organ or to enhance its functioning, says Harvard University pediatric surgeon Anthony Atala. In the case of heart failure, instead of opening the chest and surgically implanting an engineered valve or muscle tissue, he says, simply injecting the right combination of cells and signals might do the trick.

For Elisseeff and the rest of the field, the next frontier lies in a powerful new tool: stem cells. Derived from sources like bone marrow and embryos, stem cells have the ability to differentiate into numerous types of cells. Elisseeff and her colleagues have exploited that ability to grow new cartilage and bone simultaneously—one of the trickiest feats in tissue engineering. They made layers of a polymer-and-stem-cell mixture, infusing each layer with specific chemical signals that triggered the cells to develop into either bone or cartilage. Such hybrid materials would simplify knee replacement surgeries, for instance, that require surgeons to replace the top of the shin bone and the cartilage above it.

Don't expect tissue engineers to grow entire artificial organs anytime soon. Elisseeff, for one, is aiming for smaller advances that will make tissue engineering a reality within the decade. For the thousands of U.S. patients who need new joints every year, such small feats could be huge.
—*Alexandra M. Goho*

OTHERS IN INJECTABLE TISSUE ENGINEERING

RESEARCHER	PROJECT
Anthony Atala, Harvard Medical School	Cartilage
Jim Burns, Genzyme	Cartilage
Antonios Mikos, Rice U.	Bone and cardiovascular tissue
David Mooney, U. Michigan	Bone and cartilage

PAUL ALIVISATOS

Nano Solar Cells

The sun may be the only energy source big enough to wean us off fossil fuels. But harnessing its energy depends on silicon wafers that must be produced by the same exacting process used to make computer chips. The expense of the silicon wafers raises solar-power costs to as much as 10 times the price of fossil fuel generation—keeping it an energy source best suited for satellites and other niche applications.

Paul Alivisatos, a chemist at the University of California, Berkeley, has a better idea: he aims to use nanotechnology to produce a photovoltaic material that can be spread like plastic wrap or paint. Not only could the nano solar cell be integrated with other building materials, it also offers the promise of cheap production costs that could finally make solar power a widely used electricity alternative.

Alivisatos's approach begins with electrically conductive polymers. Other researchers have attempted to concoct solar cells from these plastic materials (see "Solar on the Cheap," *TR January/February 2002*), but even the best of these devices aren't nearly efficient enough at converting solar energy into electricity. To improve the efficiency, Alivisatos and his coworkers are adding a new ingredient to the polymer: nanorods, bar-shaped semiconducting inorganic crystals measuring just seven nanometers by 60 nanometers. The result is a cheap and flexible material that could provide the same kind of efficiency achieved with silicon solar cells. Indeed, Alivisatos hopes that within three years, Nanosys—a Palo Alto, CA, startup he cofounded—will roll out a nanorod solar cell that can produce energy with the efficiency of silicon-based systems.

The prototype solar cells he has made so far consist of sheets of a nanorod-polymer composite just 200 nanometers thick. Thin layers of an electrode sandwich the composite sheets. When sunlight hits the sheets, they absorb photons, exciting electrons in the polymer and the nanorods, which make up 90 percent of the composite. The result is a useful current that is carried away by the electrodes.

Looking to the sun: Paul Alivisatos hopes nanorods will boost solar-cell efficiency.
PHOTOGRAPH BY TIMOTHY ARCHIBALD

Early results have been encouraging. But several tricks now in the works could further boost performance. First, Alivisatos and his collaborators have switched to a new nanorod material, cadmium telluride, which absorbs more sunlight than cadmium selenide, the material they used initially. The scientists are also aligning the nanorods in branching assemblages that conduct electrons more efficiently than do randomly mixed nanorods. "It's all a matter of processing," Alivisatos explains, adding that he sees "no inherent reason" why the nano solar cells couldn't eventually match the performance of top-end, expensive silicon solar cells.

The nanorod solar cells could be rolled out, ink-jet printed, or even painted onto surfaces, so "a billboard on a bus could be a solar collector," says Nanosys's director of business development, Stephen Empedocles. He predicts that cheaper materials could create a $10 billion annual market for solar cells, dwarfing the growing market for conventional silicon cells.

Alivisatos's nanorods aren't the only technology entrants chasing cheaper solar power. But whether or not his approach eventually revolutionizes solar power, he is bringing novel nanotechnology strategies to bear on the problem. And that alone could be a major contribution to the search for a better solar cell. "There will be other research groups with clever ideas and processes—maybe something we haven't even thought of yet," says Alivisatos. "New ideas and new materials have opened up a period of change. It's a good idea to try many approaches and see what emerges."

Thanks to nanotechnology, those new ideas and new materials could transform the solar cell market from a boutique source to the Wal-Mart of electricity production. —*Eric Scigliano*

OTHERS IN NANO SOLAR CELLS

RESEARCHER	PROJECT
Richard Friend, U. Cambridge	Fullerene-polymer composite solar cells
Michael Grätzel, Swiss Federal Institute of Technology	Nanocrystalline dye-sensitized solar cells
Alan Heeger, U. California, Santa Barbara	Fullerene-polymer composite solar cells
N. Serdar Sariciftci, Johannes Kepler U.	Polymer and fullerene-polymer composite solar cells

imagine the future

NANCY LYNCH & STEPHEN GARLAND

Software Assurance

Computers crash. That's a fact of life. And when they do, it's usually because of a software bug. Generally, the consequences are minimal—a muttered curse and a reboot. But when the software is running complex distributed systems such as those that support air traffic control or medical equipment, a bug can be very expensive, and even cost lives. To help avoid such disasters, Nancy Lynch and Stephen Garland are creating tools they hope will yield nearly error-free software.

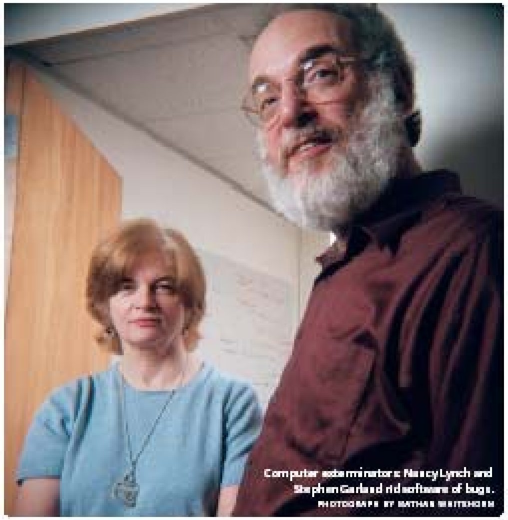
Working together at MIT's Laboratory for Computer Science, Lynch and Garland have developed a computer language and programming tools for making software development more rigorous, or as Garland puts it, to "make software engineering more like an engineering discipline." Civil engineers, Lynch points out, build and test a model of a bridge before anyone constructs the bridge itself. Programmers, however, often start with a goal and, perhaps after some discussion, simply sit down to write the software code. Lynch and Garland's tools allow programmers to model, test, and reason about software before they write it. It's an approach that's unique among efforts launched recently by the likes of Microsoft, IBM, and Sun Microsystems to improve software quality and even to simplify and improve the programming process itself.

Like many of these other efforts, Lynch and Garland's approach starts with a concept called abstraction. The idea is to begin with a high-level summary of the goals of the program and then write a series of progressively more specific statements that describe both steps the program can take to reach its goals and how it should perform those steps. For example, a high-level abstraction for an aircraft collision avoidance system might specify that corrective action take place whenever two planes are flying too close. A lower-level design might have the aircraft exchange messages to determine which should ascend and which should descend.

Lynch and Garland have taken the idea of abstraction further. A dozen years ago, Lynch developed a mathematical model that made it easier for programmers to tell if a set of abstractions would make a distributed system behave correctly. With this model, she and Garland created a computer language programmers can use to write "pseudocode" that describes what a program should do. With his students, Garland has also built tools to prove that lower levels of abstractions relate correctly to higher levels and to simulate a program's behavior before it is translated into an actual programming language like Java. By directing programmers' attention to many more possible bug-revealing circumstances than might be checked in typical software tests, the tools help assure that the software will always work properly. Once software has been thus tested, a human can easily translate the pseudocode into a standard programming language.

Not all computer scientists agree that it is possible to prove software error free. Still, says Shari Pfleeger, a computer scientist for Rand in Washington, DC, mathematical methods like Lynch and Garland's have a place in software design. "Certainly using it for the most critical parts of a large system would be important, whether or not you believe you're getting 100 percent of the problems out," Pfleeger says.

While some groups have started working with Lynch and Garland's software, the duo is pursuing a system for automatically generating Java programs from highly specified pseudocode. The aim, says Garland, is to "cut human interaction to near zero" and eliminate transcription errors. Collaborator Alex Shvartsman, a University of Connecticut computer scientist, says, "A tool like this will take us slowly but surely to a place where systems are much more dependable than they are today." And whether we're boarding planes or going to the hospital, we can all appreciate that goal. —*Erika Jonietz*



Computer exterminators: Nancy Lynch and Stephen Garland rid software of bugs.

OTHERS IN SOFTWARE ASSURANCE

RESEARCHER	PROJECT
Gerard Holzmann, Bell Labs	Software to detect bugs in networked computers
Charles Howell, Mitre	Benchmarks for software assurance
Charles Simonyi, Intentional Software	Programming tools to improve software
Douglas Smith, Kestrel Institute	Mechanized software development

imagine the future

JOHN JOANNOPOULOS

Microphotonics

Light bounces off the small yellow square that MIT physics professor John Joannopoulos is showing off. It looks like a scrap of metal, something a child might pick up as a plaything. But it isn't a toy, and it isn't metal. Made of a few ultrathin layers of non-conducting material, this photonic crystal is the latest in a series of materials that reflect various wavelengths of light almost perfectly. Photonic crystals are on the cutting edge of microphotonics: technologies for directing light on a microscopic scale that will make a major impact on telecommunications.

In the short term, microphotonics could break up the logjam caused by the rocky union of fiber optics and electronic switching in the telecommunications backbone. Photons barreling through the network's optical core run into bottlenecks when they must be converted into the much slower streams of electrons that are handled by electronic switches and routers. To keep up with the Internet's exploding need for bandwidth, technologists want to replace electronic switches with faster, miniature optical devices, a transition that is already under way *(see "The Microphotonics Revolution," TR July/August 2000).*

Because of the large payoff—a much faster, all-optical Internet—many competitors are vying to create such devices. Large telecom equipment makers, including Lucent Technologies, Agilent Technologies and Nortel Networks, as well as a number of startup companies, are developing new optical switches and devices. Their innovations include tiny micromirrors, silicon waveguides, even microscopic bubbles to better direct light.

But none of these fixes has the technical elegance and widespread utility of photonic crystals. In Joannopoulos' lab, photonic crystals are providing the means to create optical circuits and other small, inexpensive, low-power devices that can carry, route and process data at the speed of light. "The trend is to make light do as many things as possible," Joannopoulos says. "You may not replace electronics completely, but you want to make light do as much as you can."

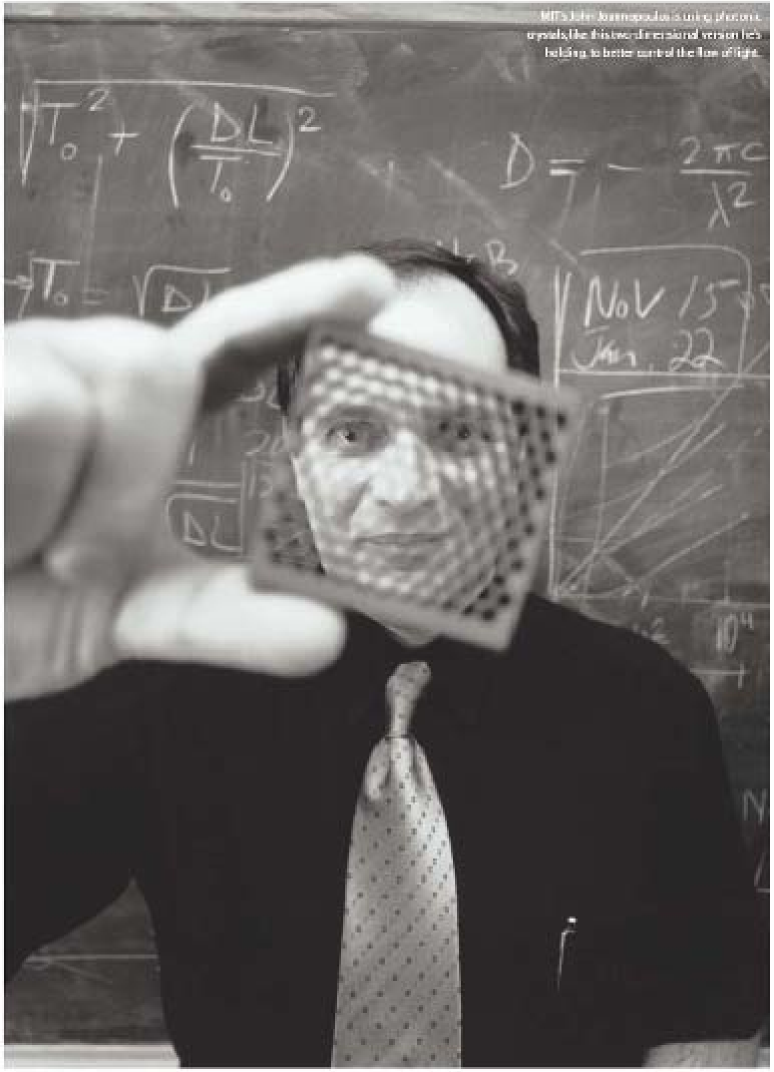
Conceived in the late 1980s, photonic crystals are to photons what semiconductors are to electrons, offering an excellent medium for controlling the flow of light. Like the doorman of an exclusive club, the crystals admit or reflect specific photons depending on their wavelength and the design of the crystal. In the 1990s, Joannopoulos suggested that defects in the crystals' regular structure could bribe the doorman, providing an effective and efficient method to trap the light or route it through the crystal.

Since then, Joannopoulos has been a pioneer in the field, writing the definitive book on the subject in 1995: *Photonic Crystals: Molding the Flow of Light.* "That's the way John thinks about it," says MIT materials scientist and collaborator Edwin Thomas. "Molding the flow of light, by confining light and figuring out ways to make light do his bidding—bend, go straight, split, come back together—in the smallest possible space."

Joannopoulos' group has produced several firsts. They explained how crystal filters could pick out specific streams of light from the flood of beams in wavelength division multiplexing, or WDM, a technology used to increase the amount of data carried per fiber *(see "Wavelength Division Multiplexing," TR March/April 1999).* The lab's work on two-dimensional photonic crystals set the stage for the world's smallest laser and electromagnetic cavity, key components in building integrated optical circuits.

But even if the dream of an all-optical Internet comes to pass, another problem looms. So far, network designers have found ingenious ways to pack more and more information into fiber optics, both by improving the fibers and by using tricks like WDM. But within five to 10 years, some experts fear it won't be possible to squeeze any more data into existing fiber optics.

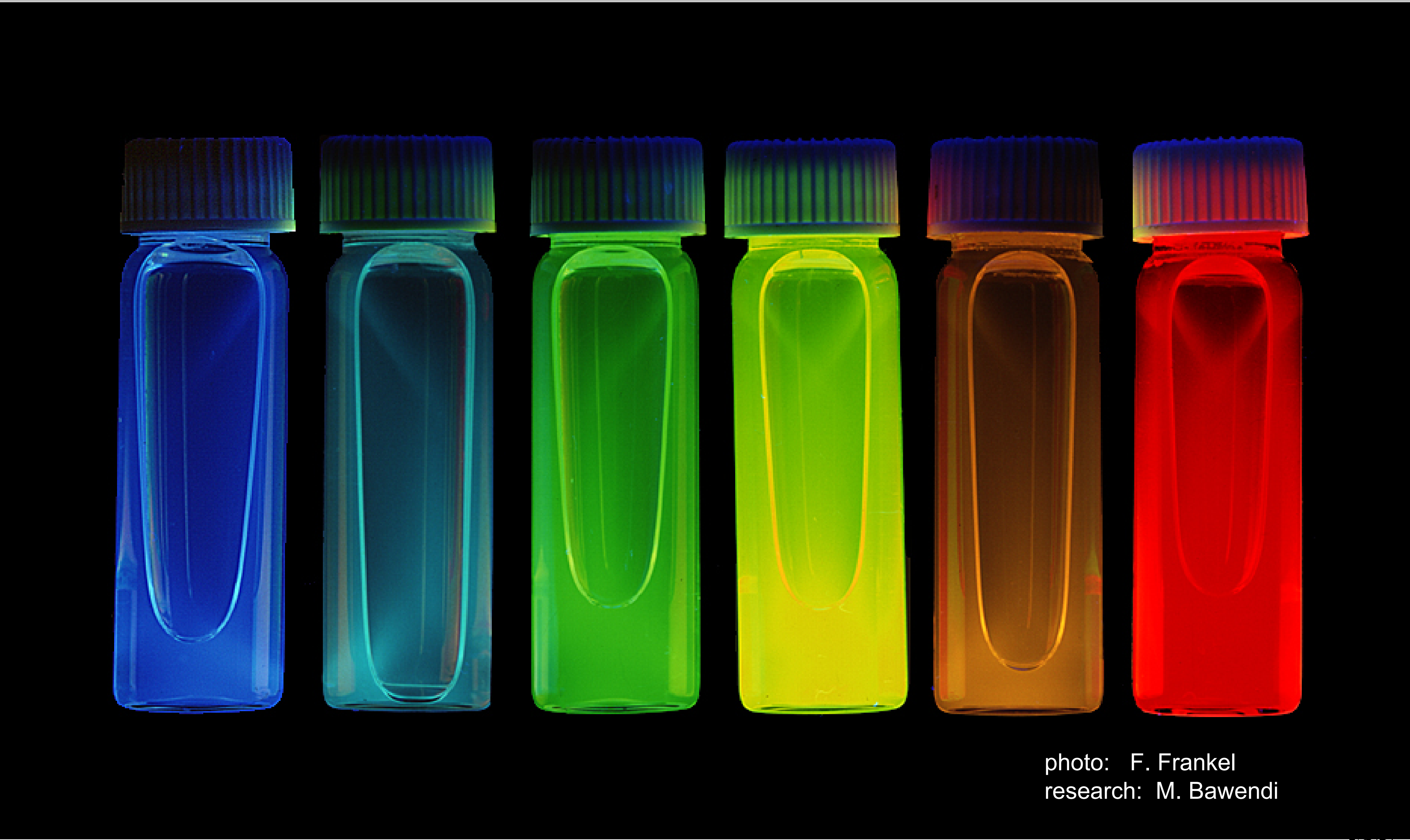
The way around this may be a type of photonic crystal recently created by Joannopoulos' group: a "perfect mirror" that reflects specific wavelengths of light from every angle with extraordinary efficiency. Hollow fibers lined with this reflector could carry up to 1,000 times more data than current fiber optics—offering a solution when glass fibers reach their limits. And because it doesn't absorb and scatter light like glass, the invention may also eliminate the expensive signal amplifiers needed every 60 to 80 kilome-



MIT's John Joannopoulos is using photonic crystals, like this two-dimensional version he's holding, to better control the flow of light.

Photograph by JOHN SOARES

Quantum dots in action



“Flatland” or “face value”

Periodic Table

1 H Hydrogen 1.0																	2 He Helium 4.0
3 Li Lithium 6.9	4 Be Beryllium 9.0											5 B Boron 10.8	6 C Carbon 12.0	7 N Nitrogen 14.0	8 O Oxygen 16.0	9 F Fluorine 19.0	10 Ne Neon 20.2
11 Na Sodium 23.0	12 Mg Magnesium 9.0											13 Al Aluminum 27.0	14 Si Silicon 28.1	15 P Phosphorus 31.0	16 S Sulfur 32.1	17 Cl Chlorine 35.5	18 Ar Argon 40.0
19 K Potassium 39.1	20 Ca Calcium 40.2	21 Sc Scandium 45.0	22 Ti Titanium 47.9	23 V Vanadium 50.9	24 Cr Chromium 52.0	25 Mn Manganese 54.9	26 Fe Iron 55.9	27 Co Colbalt 58.9	28 Ni Nickel 58.7	29 Cu Copper 63.5	30 Zn Zinc 65.4	31 Ga Gallium 69.7	32 Ge Germanium 72.6	33 As Arsenic 74.9	34 Se Selenium 79.0	35 Br Bromine 79.9	36 Kr Krpton 83.8
37 Rb Rubidium 85.5	38 Sr Strontium 87.6	39 Y Yttrium 88.9	40 Zr Zirconium 91.2	41 Nb Niobium 92.9	42 Mo Molybdenum 95.9	43 Tc Technetium 99	44 Ru Ruthenium 101.0	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3
55 Cs Caesium 132.9	56 Ba Barium 137.4	57-71	72 Hf Hafnium 178.5	73 Ta Tantalum 181.0	74 W Tungsten 183.9	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium 210.0	85 At Astatine 210.0	86 Rn Radon 222.0
87 Fr Francium 223.0	88 Ra Radium 226.0	89-103	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 263	107 Bh Bohrium 262	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Uun Ununnilium 272								

57 La Lanthanum 138.9	58 Ce Cerium 140.1	59 Pr Praseodymium 140.9	60 Nd Neodymium 144.2	61 Pm Promethium 147.0	62 Sm Samarium 150.4	63 Eu Europium 152.0	64 Gd Gadolinium 157.3	65 Tb Terbium 158.9	66 Dy Dysprosium 162.5	67 Ho Holmium 164.9	68 Er Erbium 167.3	69 Tm Thulium 168.9	70 Yb Ytterbium 173.0	71 Lu Lutetium 175.0
89 Ac Actinium 132.9	90 Th Thorium 232.0	91 Pa Protactinium 231.0	92 U Uranium 238.0	93 Np Neptunium 237.0	94 Pu Plutonium 242.0	95 Am Americium 243.0	96 Cm Curium 247.0	97 Bk Berkelium 247.0	98 Cf Californium 251.0	99 Es Einsteinium 254.0	100 Fm Fermium 253.0	101 Md Mendelevium 256.0	102 No Nobelium 254.0	103 Lr Lawrencium 257.0

Types of Elements Key:

- Alkali metals
- Alkaline earth metals
- Transition metals
- Lanthanides
- Actinides
- Poor metals
- Semi-metals
- Non-metals
- Noble gases

Outline of today's talk

- what is engineering?
- the future
- undergraduate education
  - MIT science core
  - MIT Materials Science S.B.

MIT Degree Requirements for S.B.

1st year common to all students

Engineering major 2nd, 3rd, & 4th years

6 Science Core subjects

18 Engineering subjects in the Major

8 Humanities, Arts, Social Sciences

☞ 4 subjects / semester

MIT Science Core

mathematics:	2 semesters
physics:	2 semesters
chemistry:	**1 semester**
biology:	1 semester

satisfying the chemistry requirement

- ❒ Principles of Chemical Science (5.111)

  taught by Dept. of Chemistry (5.112)

  - **focus is the molecule**

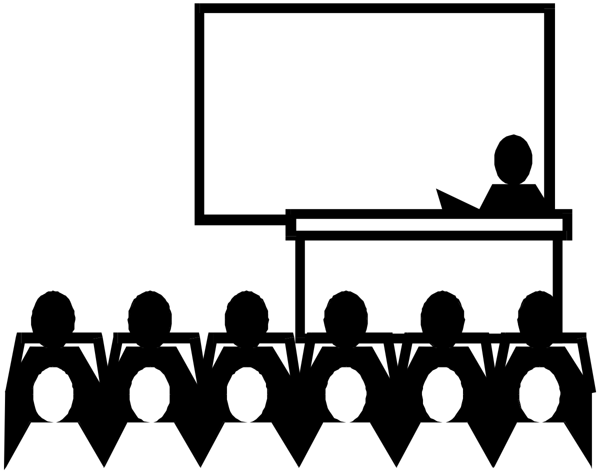
- ☑ Intro to Solid-State Chemistry (3.091)

  taught by DMSE

  - **focus is aggregates of molecules**

The vision of 3.091

- prepares students for their majors
- provides technical literacy



3.091 instruction

- teaches the principles of chemistry via the solid state
  - ☞ engineering applications
- integrates subject matter from beyond chemistry
  - ☞ context

3.091 overarching theme

electronic structure

↓

chemical bonding

↓

atomic arrangement

syllabus of 3.091

❶. General Principles of Chemistry

❷. Solid State Chemistry:

Basic Concepts and Applications

syllabus of 3.091

* Introduction: taxonomy, stoichiometry
* Evolution of atomic theory: Bohr model of hydrogen, Bohr-Sommerfeld model and multi electron atoms, atomic spectra, Heisenberg, de Broglie, Schrödinger
* The Periodic Table, Aufbau principle, Pauli exclusion principle, and Hund's rules

syllabus of 3.091

* Primary Bonding: ionic, covalent, metallic, van der Waals
* Secondary Bonding: dipole-dipole, dipole-induced dipole, London dispersion, hydrogen
* The Shapes of Molecules: electron domain theory
* Organic Compounds: nomenclature

syllabus of 3.091

* Crystal Structure: 7 crystal systems,
  14 Bravais lattices, cubic crystals
* Characterization of Structure: x-rays,
  electrons, neutrons
* Band Theory: semiconductors and devices
* Imperfections in Solids: point, line, surface
* Amorphous Solids: inorganic glasses (oxides,
  metallic); organic glasses (polymers)

syllabus of 3.091

* Solutions: solubility rules, acids, bases, pH
* Biochemistry: amino acids, peptides and proteins, lipids, nucleic acids, protein biosynthesis
* Oxidation-Reduction Reactions: electrochemistry, corrosion, batteries & fuel cells
* Reaction Kinetics: rate laws, order of reaction, effect of temperature
* Diffusion: Fick's first and second laws
* Phase Stability: unary and binary phase diagrams

omissions from 3.091 syllabus

* Thermodynamics: heats of formation, entropy, free energy, chemical equilibria

* Coordination compounds: crystal field theory, ligand field theory, organometallic chemistry

* Lighter treatment of acids & bases, chemical kinetics, electrochemistry

Snapshot of 3.091 Fall 2003

enrollment **625** (class size **1015**)

lectures MWF (chalk & talk w/ AVs)

recitations TR (30 sections)

weekly sample problems w/ solutions

weekly 10-minute quiz

time to reflect

monthly test (aid sheet)

final exam (aid sheet)

Special Features of 3.091

- ❐ concepts illustrated by examples
- ❐ last 5 minutes each lecture on
  Chemistry and the World Around Us
- ❐ references to music, art, film, & literature
- ❐ references to historical development of science:
  people & times

☞ ***context***

Chemistry & the World Around Us

- industrial practice – **environmental** impacts of processes (**metals extraction**) & products (**automobiles**)
- energy generation and storage – **fuel cells & batteries**
- emerging technologies – **photonic devices & biomaterials**
- current research – at MIT and elsewhere

Chemistry and Music

aqueous solutions: ***Water Music***

band theory of solids: ***In the Mood, AC/DC***

Moseley's law: ***Rondo alla Turca; Istanbul not Constantinople***

de Broglie, Heisenberg, Schrödinger:

Catch a Wave; Mack the Knife; Smooth Operator

Mendeléev's periodic law: ***Polovtsian Dance № 17***

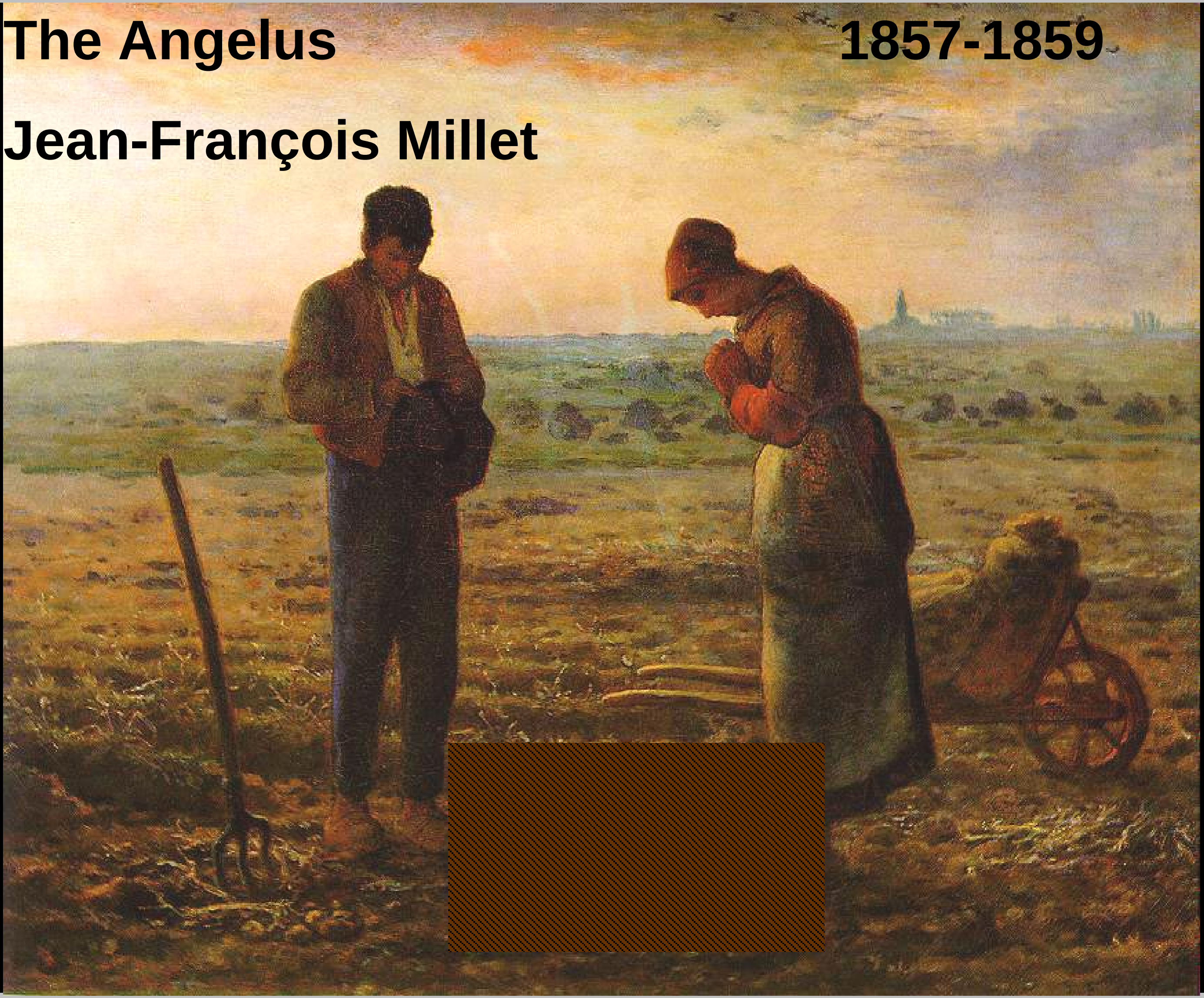
x-rays: ***Love Theme from Superman, Andrea Chenier***

quasicrystals: ***Take Five***

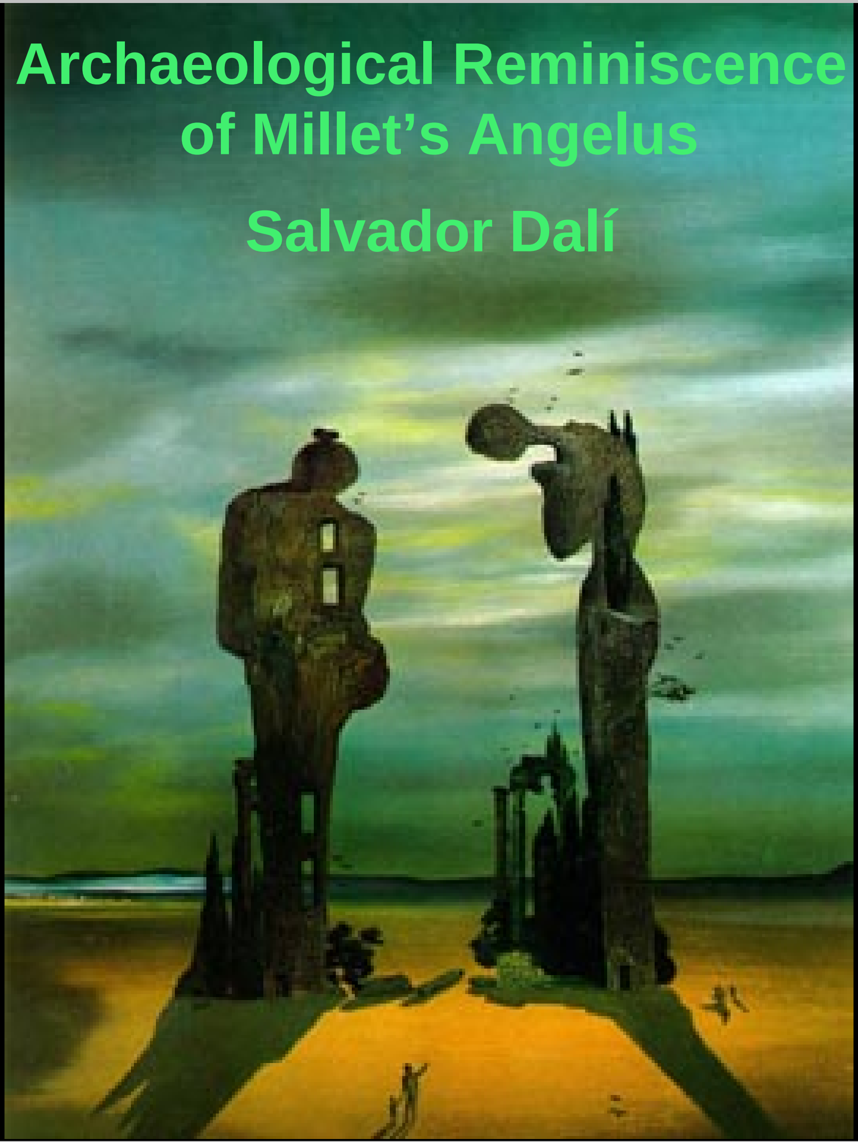
polymers: ***Chain of Fools***

DNA: ***The Twist***

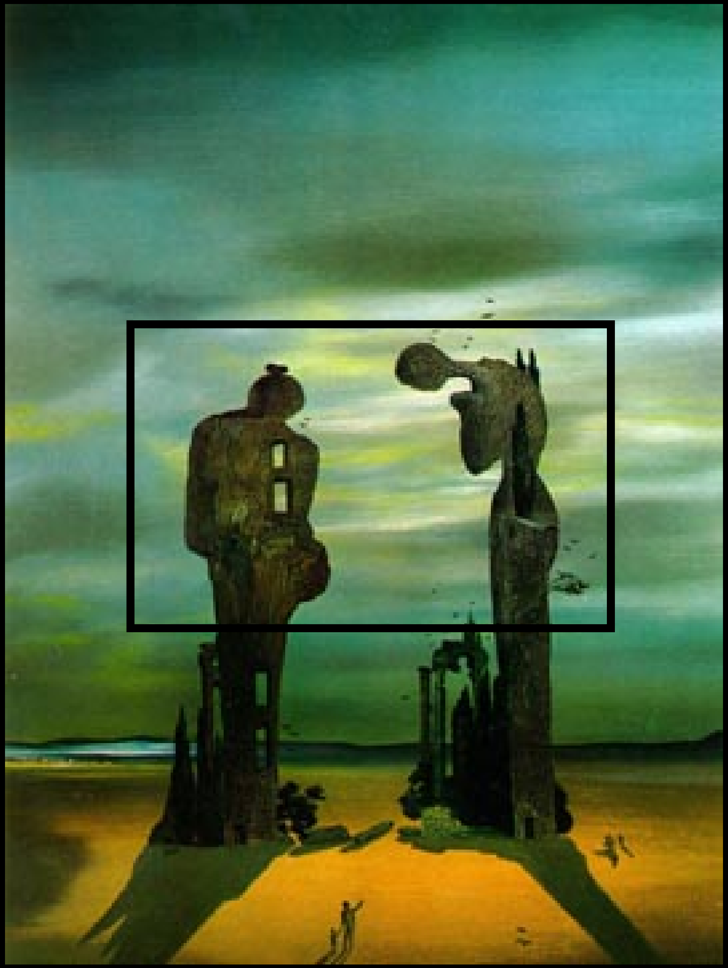
Chemistry and Art

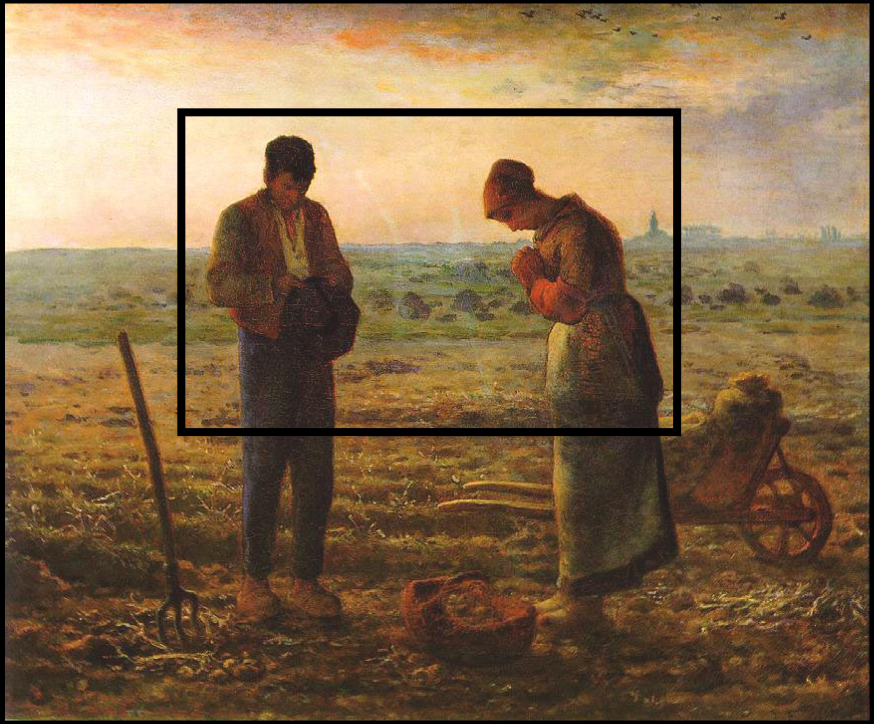


Chemistry and Art



Chemistry and Art

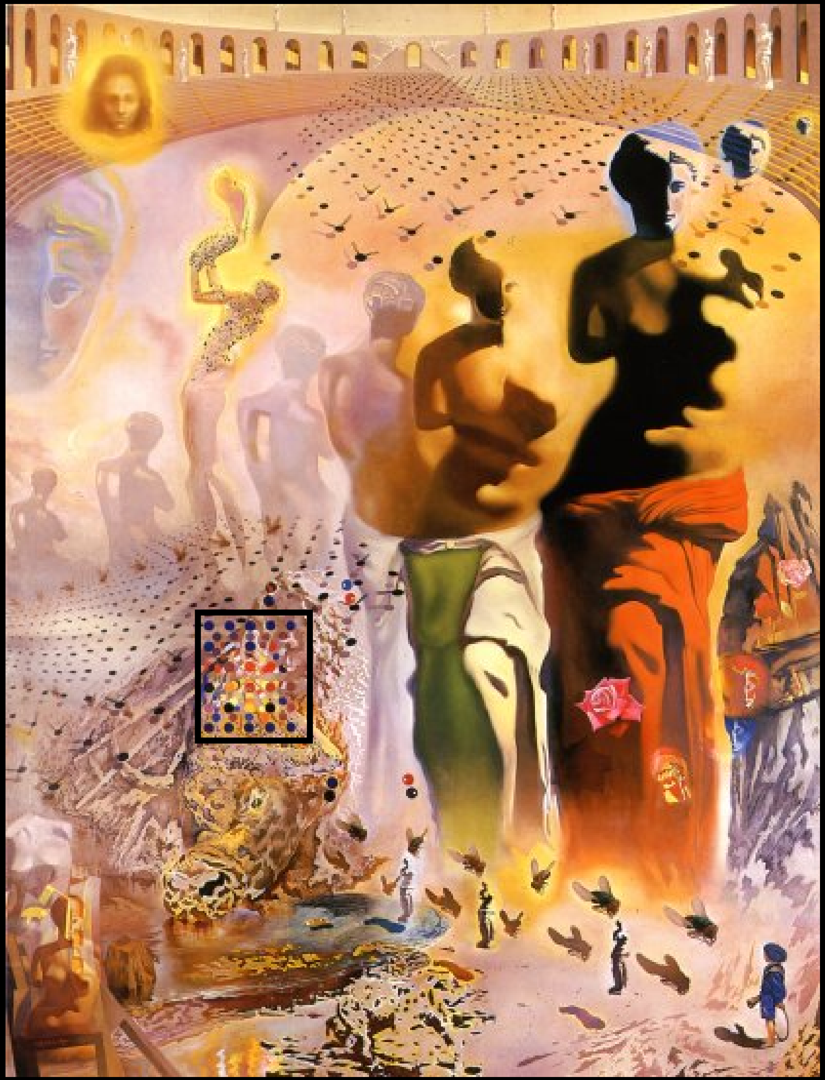


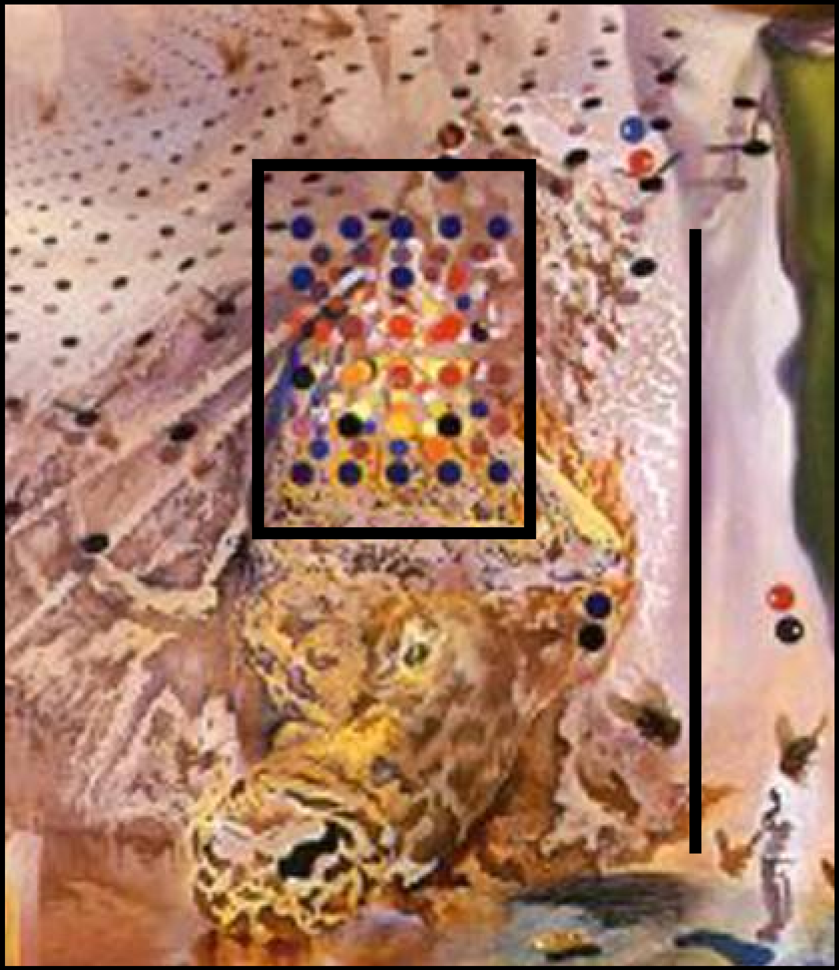


Chemistry and Art

The Hallucinogenic Toreador

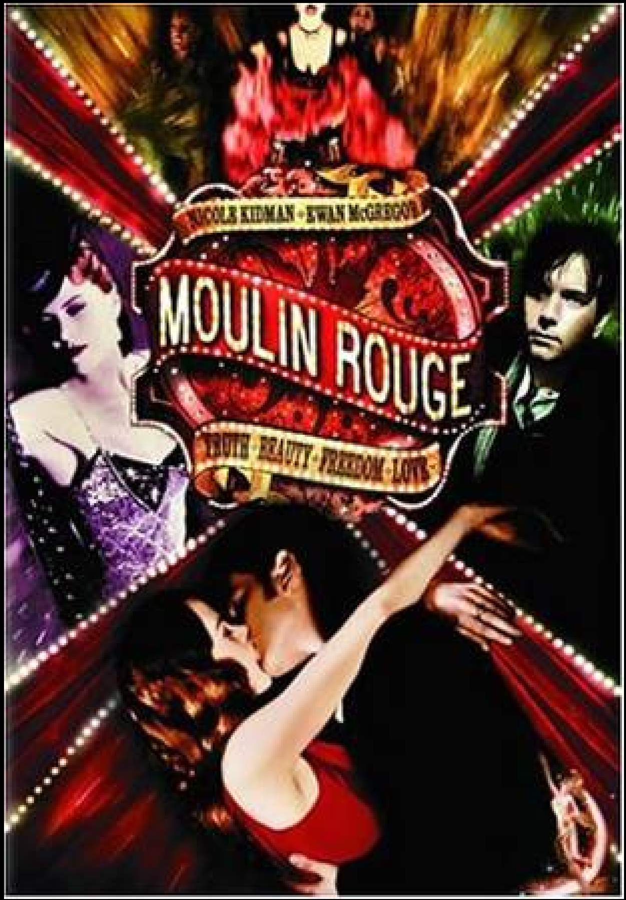
Chemistry and Art





Chemistry and Film

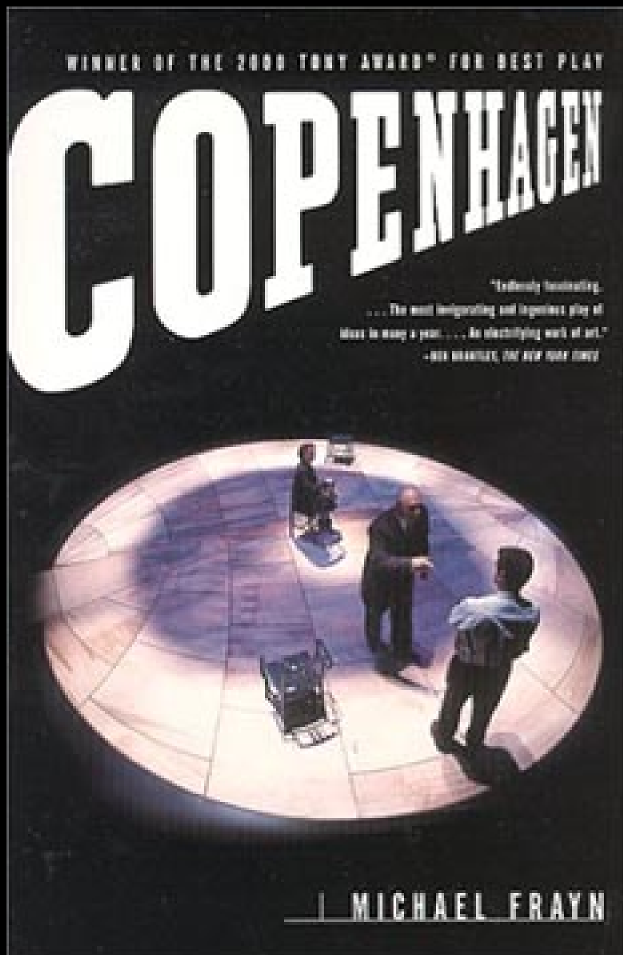
the quintessential polymer reference

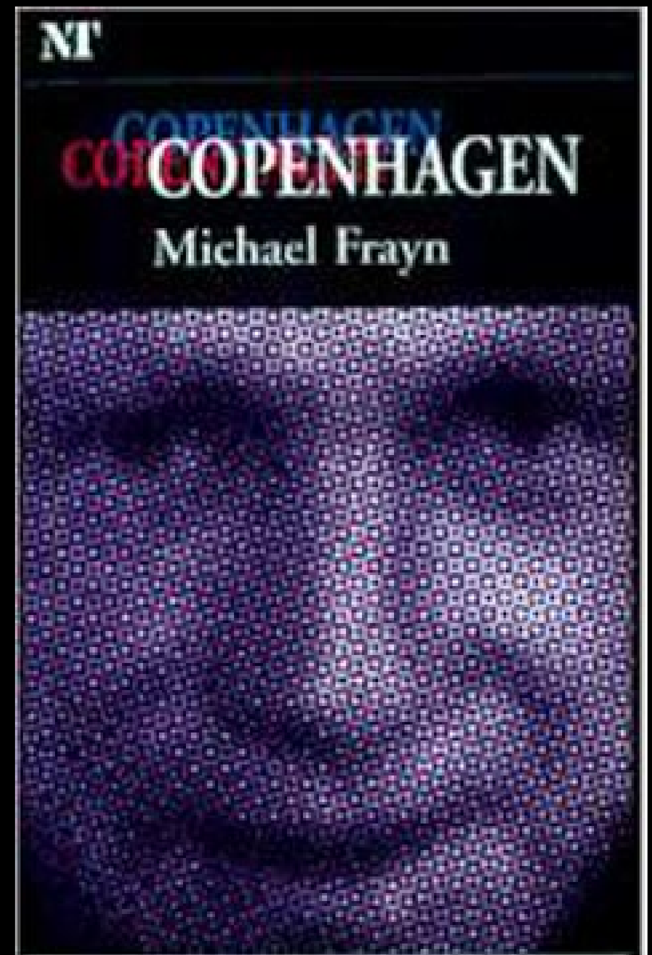


absinthe + water: partial solubility

Chemistry and Literature

Tony Award winner 2000





Nobelists we have met in 3.091

Röntgen	1901	Physics
Zeeman	1902	
J.J. Thomson	1906	
van der Waals	1910	
von Laue	1914	
the Braggs	1915	
Planck	1918	
Einstein	1921	
Bohr	1922	
de Broglie	1929	
Heisenberg	1932	
Schrödinger	1933	
Davisson	1937	
Pauli	1945	
Bloch	1952	
Born	1954	

Nobelists we have met in 3.091

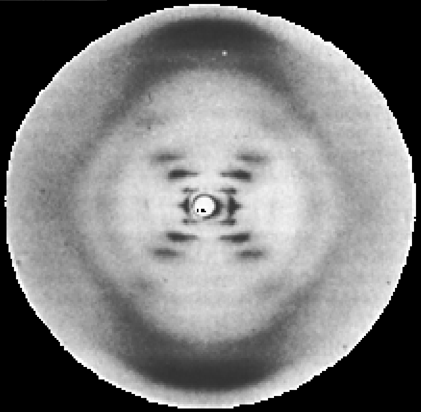
Arrhenius	1903	Chemistry
Rutherford	1908	
Haber	1918	
Nernst	1920	
Urey	1934	
Debye	1936	
Hahn	1944	
Seaborg	1951	
Pauling	1954	
Libby	1960	
Watson, Crick, Wilkins	1954	Medicine

Historical development of science: people & times

Women in science: STUDIES OF ABUSE

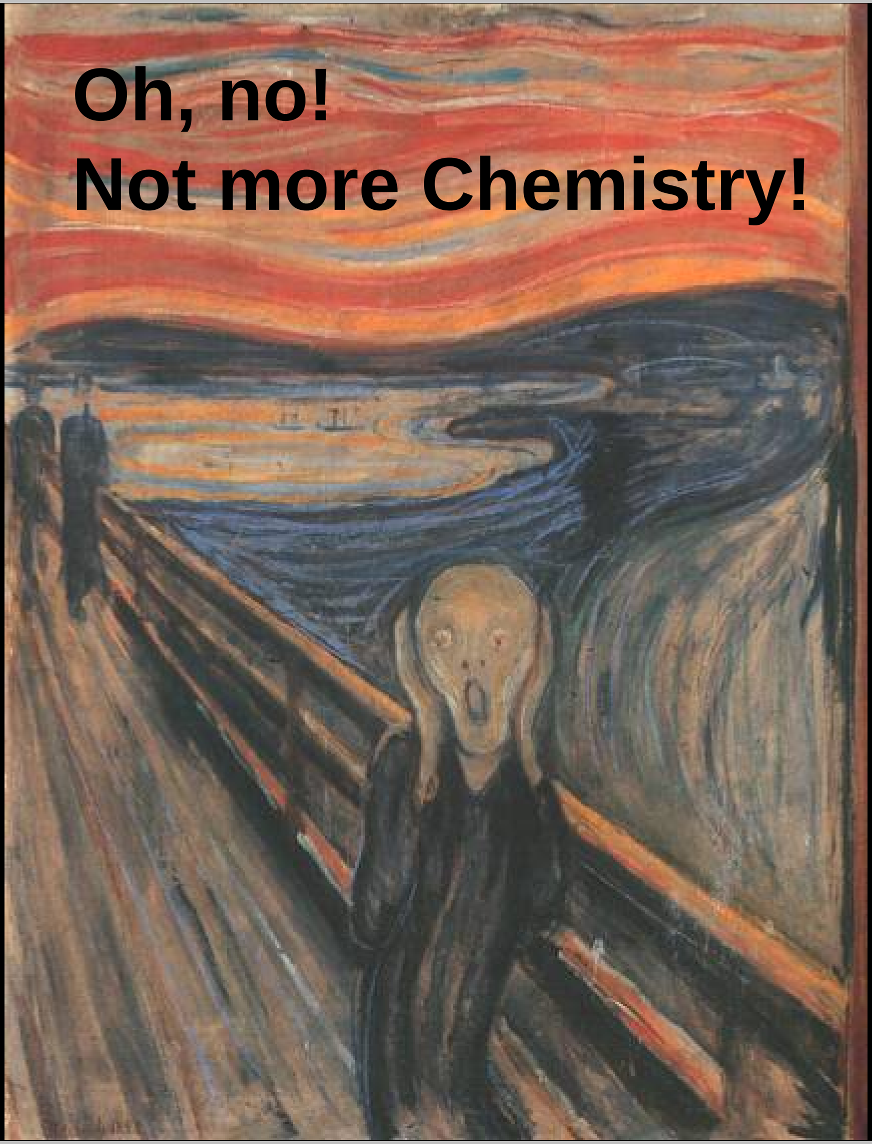
- ✪ Cecilia Payne:
  the Sun is made of hydrogen

- ✪ Lisa Meitner:
  nuclear fission



- ✪ Rosalind Franklin:
  the structure of DNA

Student reaction? Before 3.091:



Student reaction now:

625 / 900 chose 3.091

➪ **recruitment**

- DMSE

- SoE

- MIT

generalizing the 3.091 experience

Why? The science core fails to measure up.

- big shift after WWII from craft-based to science-based engineering education
- new science classes taught by science faculty
- student reaction today: ☹ ☠ ⌛ 💣

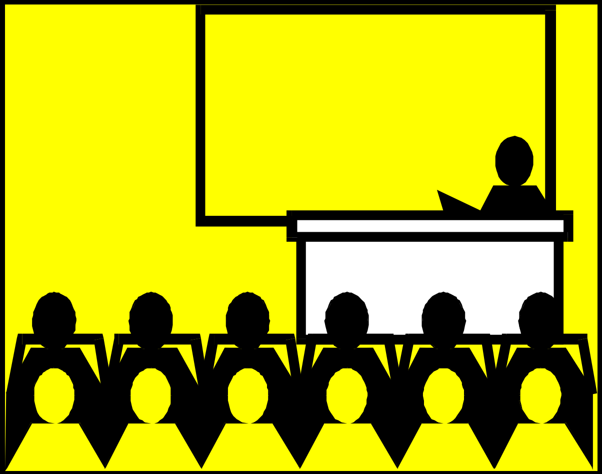
generalizing the 3.091 experience

Engineering faculty need to shape the science core.

- What constitutes engineering science in the 21st century?
- The education of engineering students must no longer be subordinated to “entitlements.”

Next steps

- companion HASS subject 21.021
  - ☞ towards still greater curricular integration



21.021 syllabus

Lecture 1: Nature of Humanities, The Task of Writing, The Dream of Order.
Reading: Lambuth, The Golden Book on Reading, 1-43; Steven Shapin, "Pump and Circumstance", Social Studies of Science, 14 (1984), 481-520

Lecture 2: Trust.
Reading: Arthur Conan Doyle, "The Adventure of the Three Students", 12pp.; Harry Collins, "Ch. 3: Replicating the TEA-Laser", Changing Order – Replication and Induction in Scientific Practice, 51-78; Arne Hessenbruch, "Calibration and Work in the X-ray Economy, 1896-1928", Social Studies of Science, 30 (June 2000), 397-420.

Lecture 3: Politics.
Reading: Bruno Latour, "Give me a Laboratory and I Will Raise the World", in Mario Biagioli, The Science Studies Reader, 258-275; Michael Frayn, Copenhagen. (Or watch DVD, 116minutes)

21.021 syllabus

Lecture 4: High Culture.
Reading: Peter Gay, Weimar Culture – The Outsider as Insider, Ch. 4: “The Hunger for Wholeness”, 70-101; Peter Galison, Ch. 1: “Buildings and the Subject of Science”, 1-28 in Galison and Emily Thompson (eds.), The Architecture of Science; skim through Paul Forman’s, “Weimar Culture, Causality, and Quantum Theory, 1918-1927: Adaptation by German Physicists and Mathematicians to a Hostile Intellectual Environment,” in Darwin to Einstein: Historical Studies on Science and Belief, edited by Colin Chant and John Fauvel (New York: Longman, 1980), pp. 267-302.

Lecture 5: Genius.
Reading: Robert Friedel, “Defining Chemistry: Origins of the Heroic Chemist”, in Chemical Sciences in the Modern World, edited by Seymour Mauskopf, 20pp.; A. Friedman and C. Donley, Einstein as Myth and Muse, Ch. 6: A myth portrayed, 154-195; Steven Shapin, “The Invisible Technician”, American Scientist, 77 (1989), 554-563.

21.021 syllabus

Lecture 6: The Nobel Prize and Credit.
Reading: Bishop, “The Phone Call”, Ch. 1 in How to Win the Nobel Prize, 1-36; that week’s announcements of winners on www.nobel.se; topical articles of that week in New York Times.

Lecture 7: Science and the Public.
Reading: Iwan Morus, “Two Experimental Lives: Faraday and Sturgeon”, History of Science, 30 (1992), 1-28; Arne Hessenbruch, "Science as public sphere: x-rays between spiritualism and physics", in Wissenschaft und Öffentlichkeit in Berlin, 1870-1930, edited by Constantin Goschler, Wiesbaden: Franz Steiner Verlag, 2000, 89-126.

Lecture 8: Instrumentation and Material Culture
Reading: Hong Sungook, “From Effect to Artifact: the case of the thermionic valve”, Physis 33 (1996), 85-124; Frederick Seitz, “The tangled prelude to the age of silicon electronics”, Proceedings of the American Philosophical Society, 140 (1996), 289-337.

21.021 syllabus

Lecture 9: Law and Regulation

Reading: Sheldon Krimsky, “A citizen court in the rDNA debate”, Bulletin of the Atmic Scientists, 34 (1978), 37-43; Rae Goodell, “Public involvement in the rDNA debate, the case of Cambridge, Massachusetts”, Science, Technology and Human Values, 4 (1979), 36-43; Patricia Ewick and Susan Silbey, The Common Place of Law – Stories from Everyday Life, 1-32.

Lecture 10: Risk

Reading: Harry Collins and Trevor Pinch, “The naked launch: assigning blame for the Challenger explosion”, in The Golem at large, 30-56; Charles Perrow, “Petrochemical Plants”, in Normal Accidents – Living with High-Risk Technologies, 101-122; Sheila Jasanoff, “Acceptable Evidence in a Pluralistic Society”, in Deborah Mayo and Rachelle Hollander (eds.), Acceptable Evidence – Science and Values in Risk Management, 29-47.

Next steps

Lecture 11: Large Technological Systems
Reading: Trevor Pinch and Wiebe Bijker, “The Social Construction of Facts and Artifacts”, in The Social Construction of Technological Systems, edited by Bijker et al, 17-50; Thomas Hughes, “The Evolution of Large Technical Systems”, in ibid., 51-82; see movie Man in the White Suit (76 mins).

Lecture 12: Plastics and modern chemistry.
Reading: Jeffrey Meikle, “Plastics in the American Machine Age”, in The Plastics Age, edited by Penny Sparke, 40-53; Barbara Marinacci (ed.), Linus Pauling in his own words, Ch. 2 “What is Chemistry?” 43-54, Ch. 4 “Probing the Chemical Bond” 67-90, Ch. 6 “Proteins Revealed” 112-134.

Lecture 13: Science Fiction
Reading: Michael Crichton: Prey, pp. 1-30 (try not to finish it!); H. G. Wells, “The Time Machine”, Selected Short Stories, Penguin, 1979, 7-84 ; Donna Haraway, “Cyborg Manifesto”, in Simians, Cyborgs, and Women: The Re-invention of Nature, 149-181.

21.021 syllabus

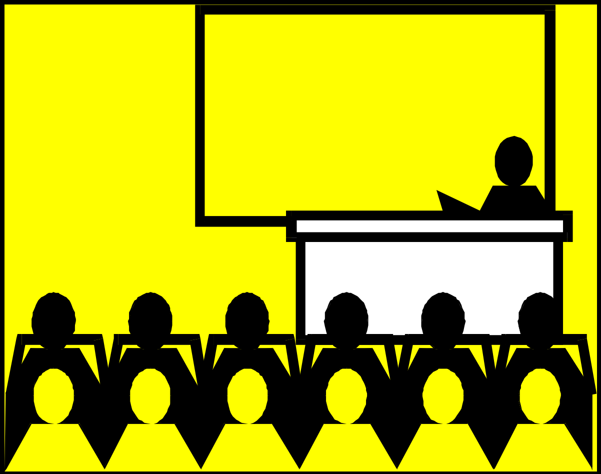
Lecture 14: Gender and Race
Reading: Haramundanis (ed.), Cecilia Payne-Gaposchkin: An Autobiography and Other Recollections, “Part IV: Reflections”, 217-238; Evelyn Fox-Keller, “How gender matters”, in Gill Kirkup and Laurie Smith Keller (eds.), Inventing Women – Science, Technology and Gender, 42-56; Steven Rose et al, Not in Our Genes, Chs. 1 & 2 “The New Right and the Old Determinism” and “The Politics of Biological Determinism” 3-36.

Lecture 15: Overview and Conclusion.

Still more next steps

- laboratory accompaniment via Materials Digital Library:

  how many of the educational benefits can be acquired without being in the lab?



Outline of today's talk

- what is engineering?
- the future
- undergraduate education
  - MIT science core
  - MIT Materials Science S.B.

Motivation: pushes & pulls

❶ disturbing trend in enrollment

❷ dissatisfaction among students:

* feel ill prepared (weak in math, quantum mechanics, probability & statistics, *k*-space, numerical methods, data analysis, design, leadership/management)
* find program boring (too easy, lacks rigor & context)
* no clear theme (no obvious sequence, much repetition, no evident coordination)
* feel that faculty place lowest priority on u.g. program, c.f. research, consulting, committee assignments

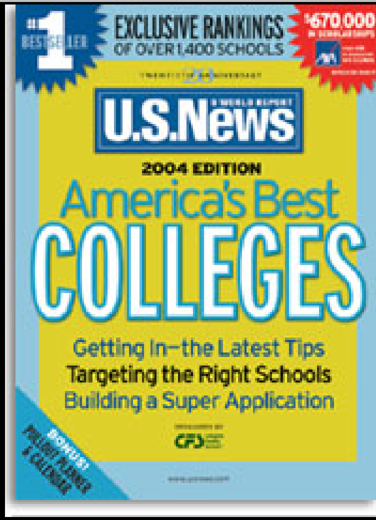
Motivation (continued)

❸ drop in ratings in *US News & World Report*

❹ advances in information systems:
implications for engineering education?

❺ renovation of Building 8: unique opportunity
☞ linking space changes to curricular changes

Motivation (continued)



❸ drop in ratings in *US News & World Report*

❹ advances in information systems:
implications for engineering education?

❺ renovation of Building 8: unique opportunity
☞ linking space changes to curricular changes

Opinions expressed by our faculty

❶ need for context, applications, problem solving, teamwork, communication skills, design-oriented laboratory

❷ prepare students for multiple career paths: grad school, terminal SB, professional schools, etc.

❸ move towards integrated education

☞ look at other departments in SoE

❹ 18.03 (differential eq^{n}s) does not meet our needs

The Process and Timeline

❶ department head (Subra Suresh) names a leader (Donald Sadoway) **6/01**

❷ brainstorming among committee members **fall 01**

❸ data gathering among different stakeholders **spring 02**

❹ committee develops draft program at the level of storyboards and presents to the entire faculty for discussion **2/02 and 5/02**

❺ faculty teams tasked to develop syllabuses for suites of subjects by semester **5/02**

The Process and Timeline

❻ adoption of syllabuses by entire faculty

☞ green light to develop subject contents at the level of lecture topics **1/03**

❼ development of subject content with close interaction with coordinators, e.g., math, lab, professional development **1/03 through present**

⓿ communication with various Institute committees to prepare for necessary approvals **1/03 through 6/03**

The Goal of a MSE Education

Our mission statement

to educate specialists

in the development and use

of materials in technology

The Course of Study

- core technical knowledge
- professional development
- capstone activity
  - ☞ meets ABET specifications

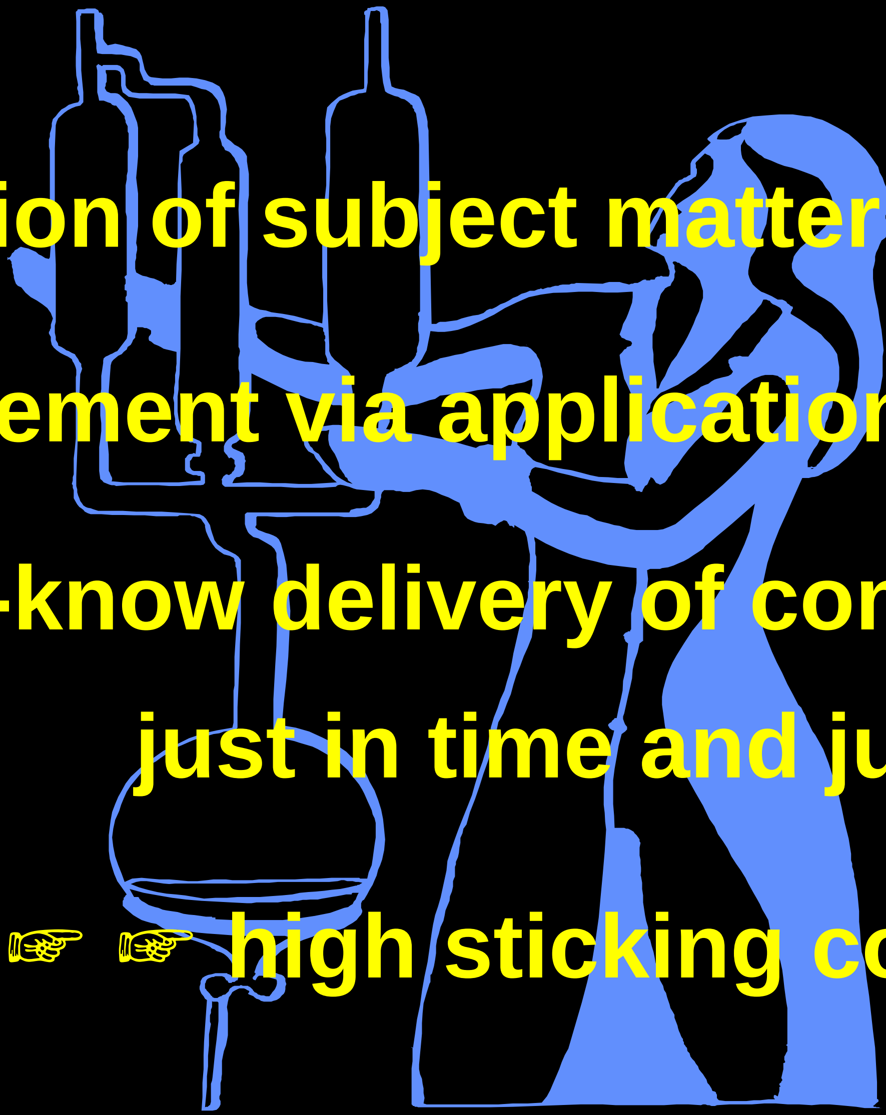
ABET's Educational Outcomes

from ***Engineering Criteria 2000***

Engineering programs must demonstrate that their graduates have:

(a) an ability to apply knowledge of mathematics, science, and engineering
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs
(d) an ability to function on multi-disciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Pedagogical Considerations

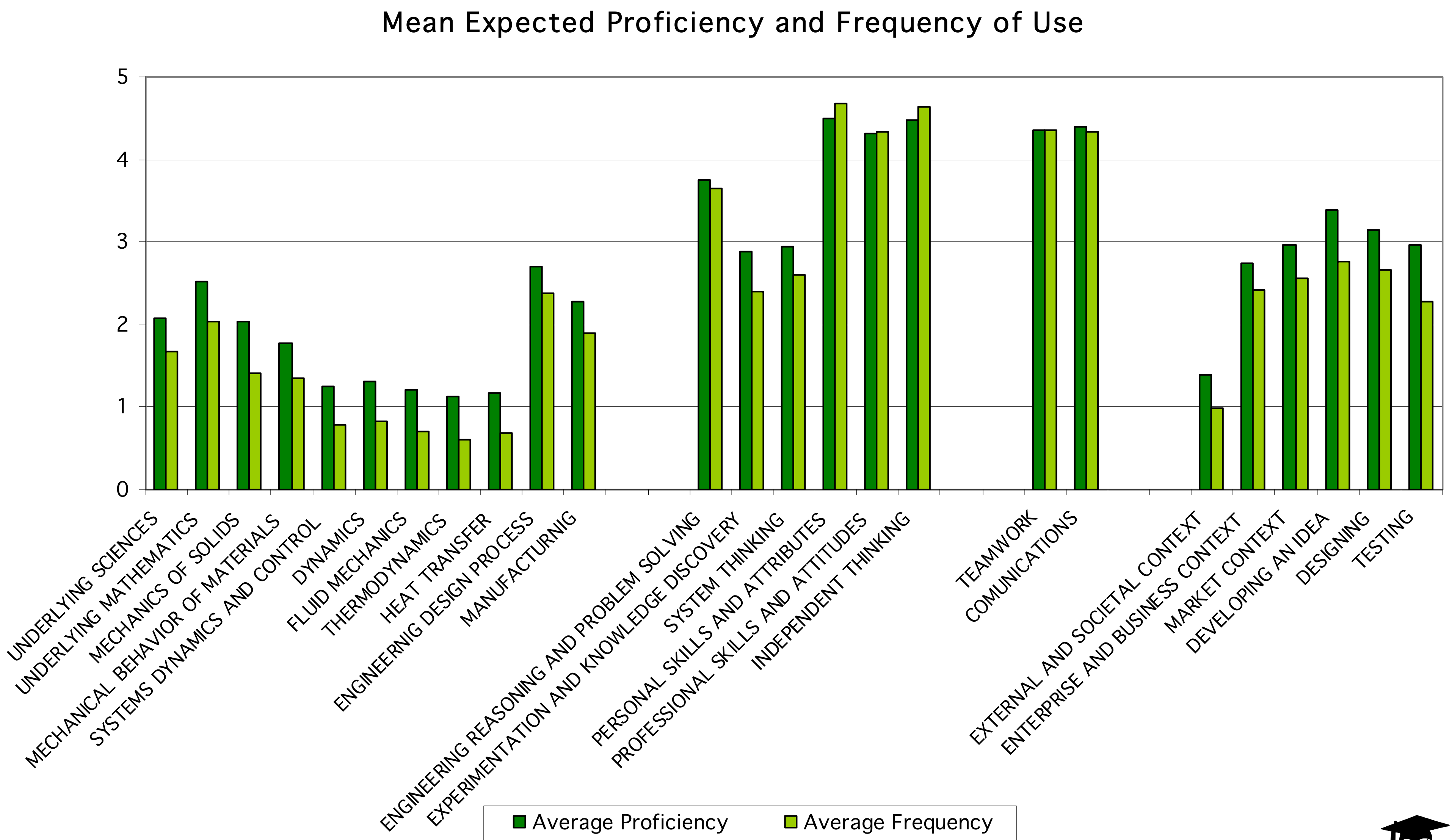


- integration of subject matter (crosstalk)
- reinforcement via application
- need-to-know delivery of content:

  just in time and just enough

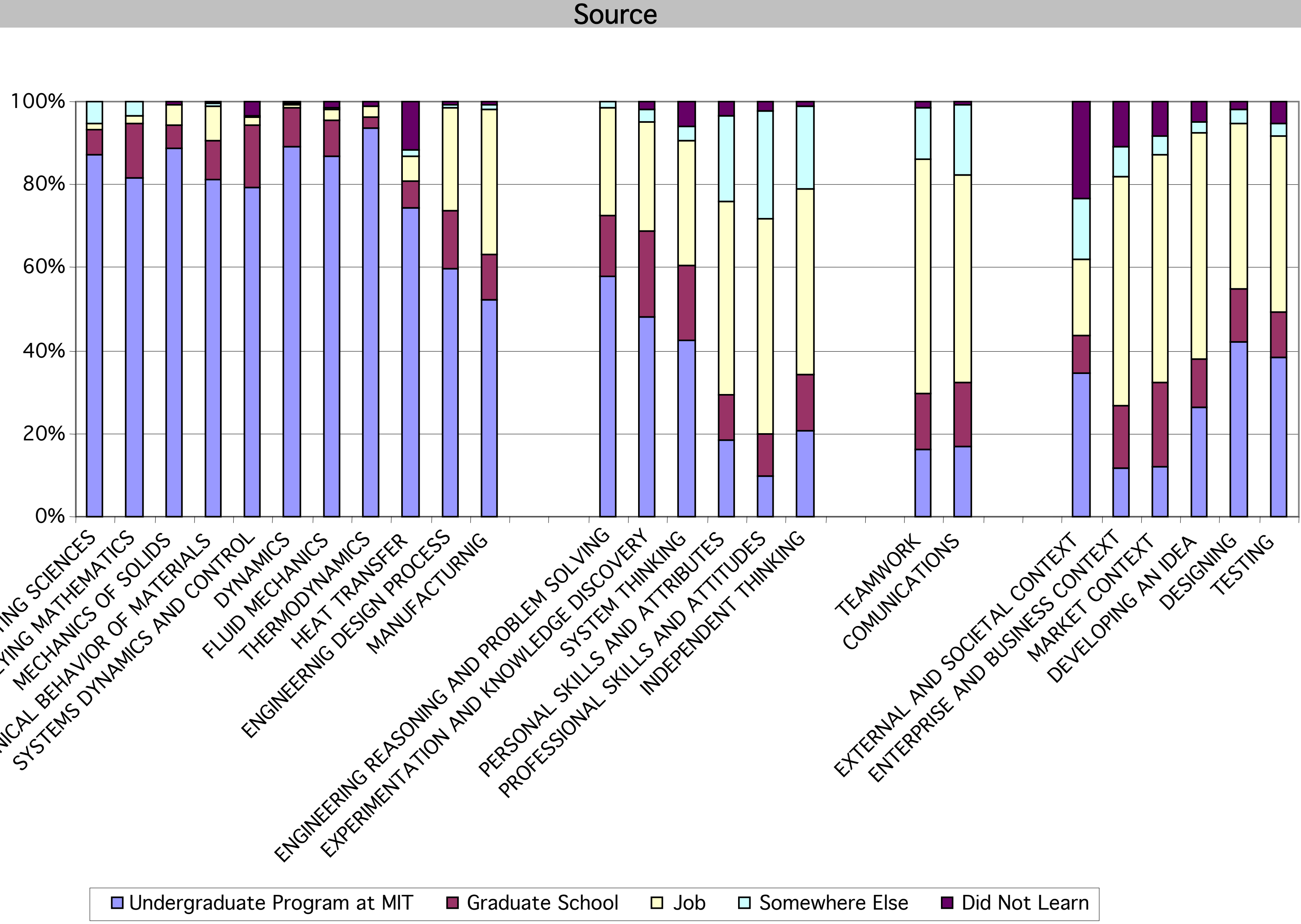
  ☞ ☞ ☞ high sticking coefficient

Alumni survey says:

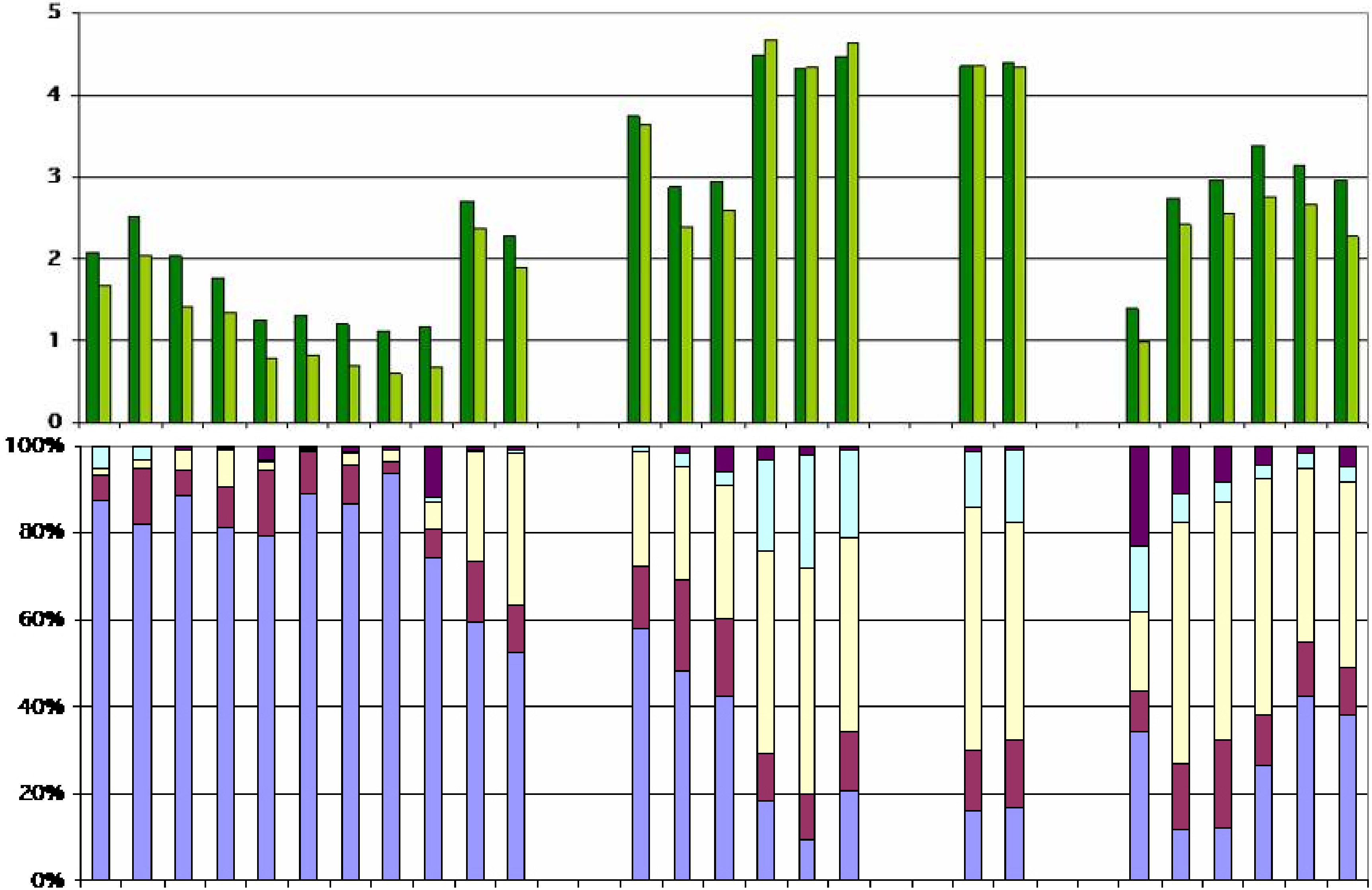


Expected Proficiency: 0 To have essentially no knowledge of, 1 To have experienced or been exposed to, 2 To be able to participate in and contribute to, 3 To be able to understand and explain, 4 To be skilled in the practice or implementation, 5 To be able to lead or innovate in

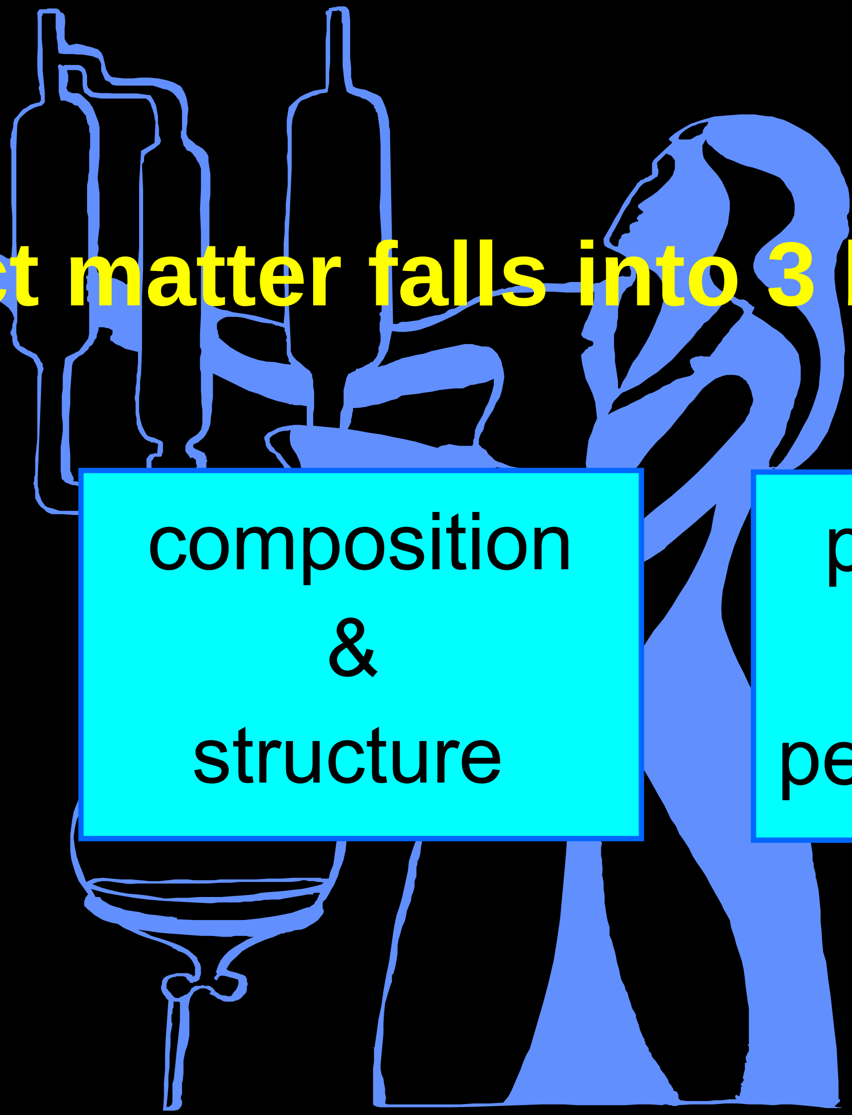
Alumni survey says:



Alumni survey says:



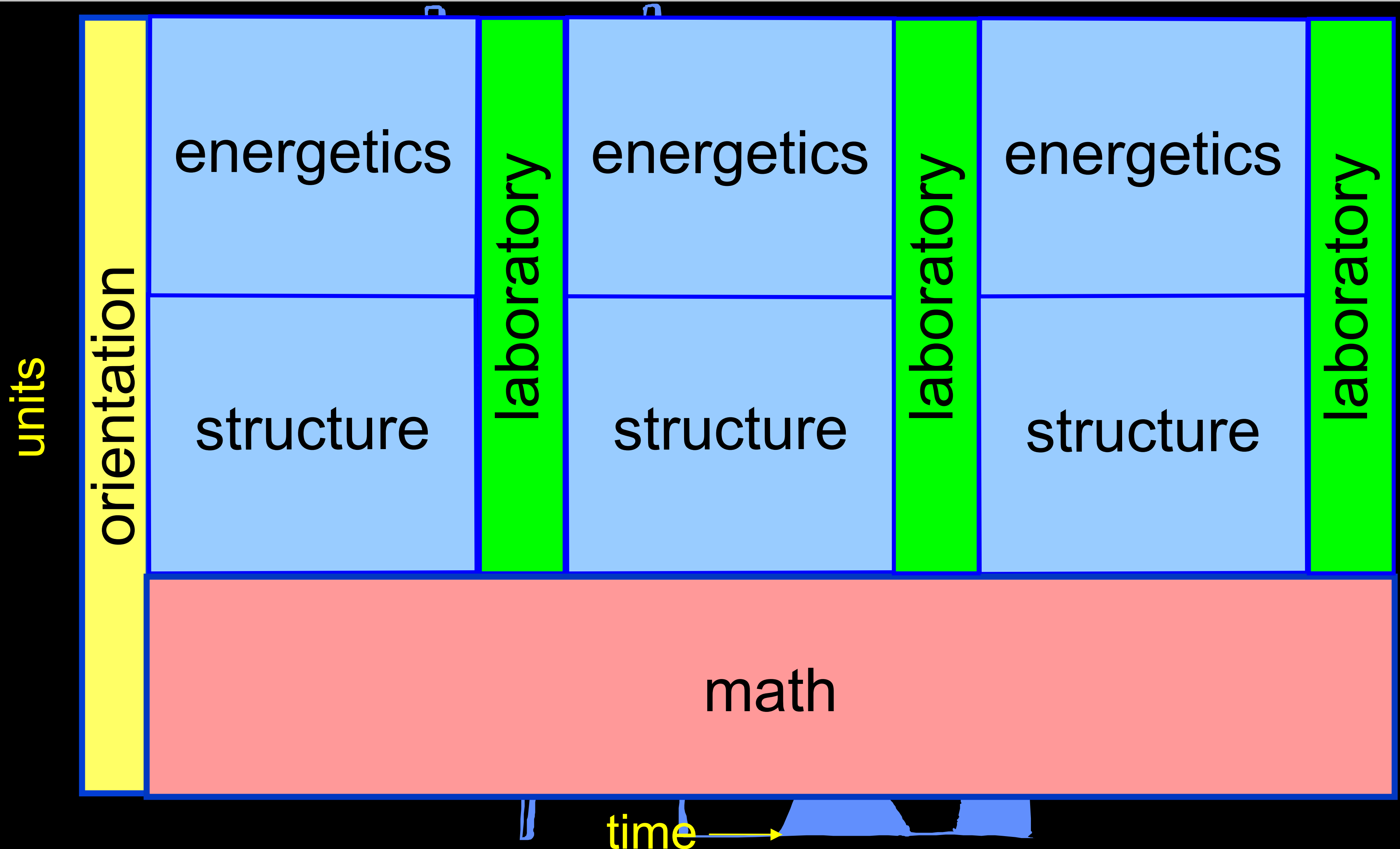
Core Technical Knowledge



subject matter falls into 3 blocks

synthesis & processing	composition & structure	properties & performance

Storyboard Fall Year 2



Schedule - Fall Year 2

Fall Y2	M	T	W	Th	F
Sept			Orientation 4	Orientation 5	Orientation 6
	9	10	11	12	13
	16	17	18	19	20
	23	24	25	26	27
Oct	30	1	2	3	4
	7	8	9	10	11
	14	15	16	17	18
	21	22	23	24	25
	28	29	30	31	1
Nov	4	5	6	7	8
	11	12	13	14	15
	18	19	20	21	22
	25	26	27	28	29
Dec	2	3	4	5	6
	9	10	11		

Laboratories

Orientation

Vacation days

Schedule - Fall Year 2

	M	T	W	R	F
9					
10	3.012		3.012		3.012
11	3.012		3.012		3.012
12					
1	3.016		3.016		3.016
2					
3					
4					

Lecture (blue)

Recitation (red)

Schedule - Fall Year 2

	M	T	W	R	F
8			3.014		3.014
9	3.014		3.014		3.014
10	3.014		3.014		3.014
11	3.014		3.014		3.014
12	3.014				
1	3.016		3.016		3.016
2					
3					
4					

Lecture (blue)

Recitation (red)

Laboratory (green)

Sample Storyboard - Fall Year 2

Orientation: What is MSE?

Materials & History

Current Trends in the field of MSE

Career Opportunities & Pathways

Unifying Theme of Course 3

- ☞ view of the “big picture”
- ☞ motivated to study fundamentals
- ☞ *esprit de corps*

← first week →

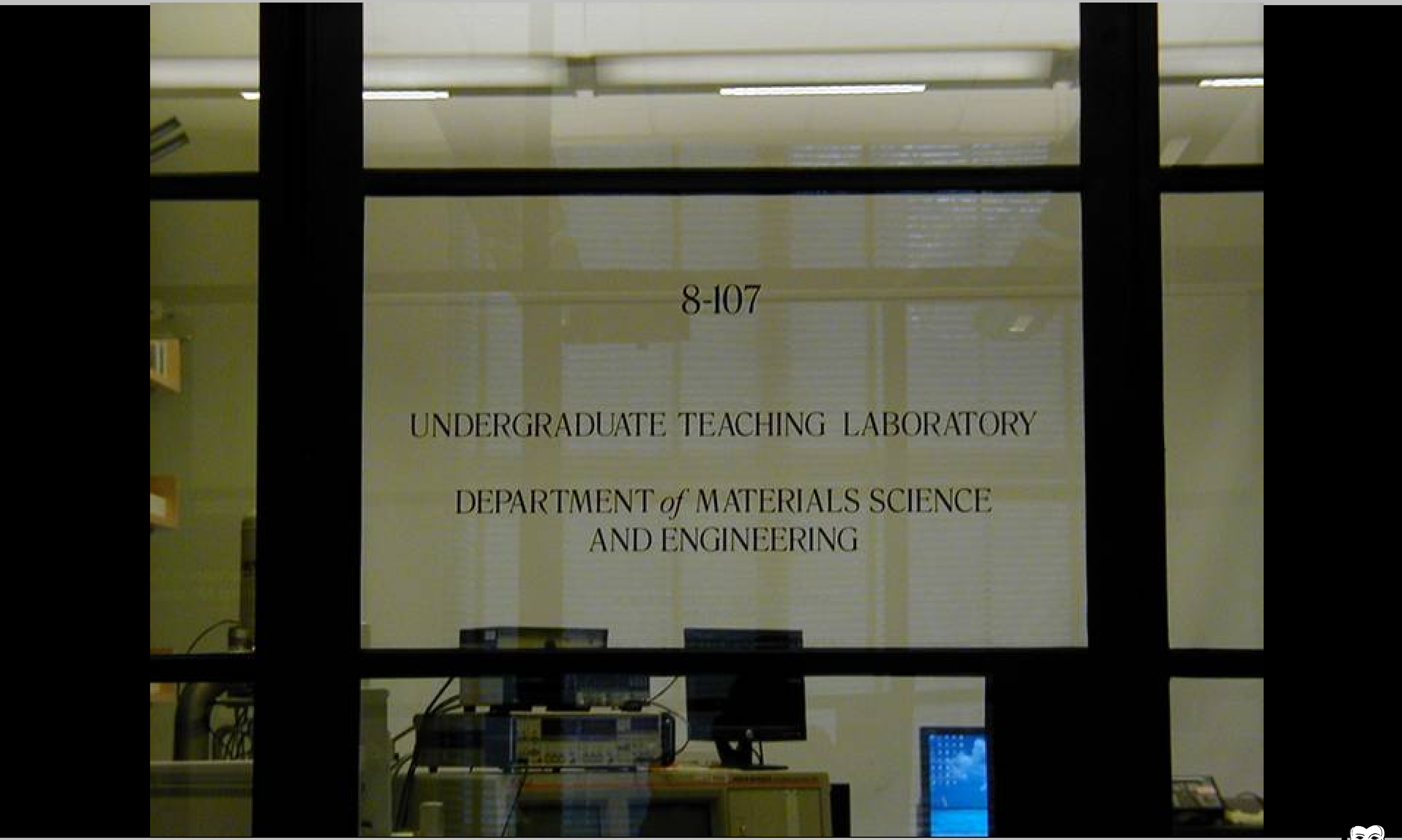
Sample Lecture Plan - Fall Year 2

09/18	Building descriptions of solids from the ground up	QUANTIZATION OF ENERGIES, AND THE BIRTH OF INTERACTIONS -boundary conditions → quantization of energies: the infinite well -well becomes finite – electrons spread out -two wells getting closer… **Application Example:** stationary waves in organ pipes and drums. Tunneling behavior of electrons (STM).	HOW DO WE CONNECT THE ATOMS AND MOLECULES OF A MATERIAL TO THERMODYNAMIC FUNCTIONS? -the use of simple models to consider many atoms in a material -introduction to microstates microstates and energy: role of heat: energy levels are fixed; occupation changes! -averaging, ensembles, and the premise of statistical mechanics (two postulates of stat mech) -our first prediction, using the microcanonical ensemble: behavior of an ideal gas **Application Example:** How does our calculation compare with the behavior of real gases?	-Multivariate calculus partial derivatives extrema of multivariate functions integrating multivariate functions Need series approximations here? -ODE -Boundary conditions -separation of variables

Laboratories

- new equipment
- ~200 m^2 additional space
- new content:
  - biomaterials
  - chemical synthesis
  - elec. mat. characterization

New Undergraduate Laboratory



New Undergraduate Laboratory

Compare to this typical scene

Compare to this typical scene

Much better!

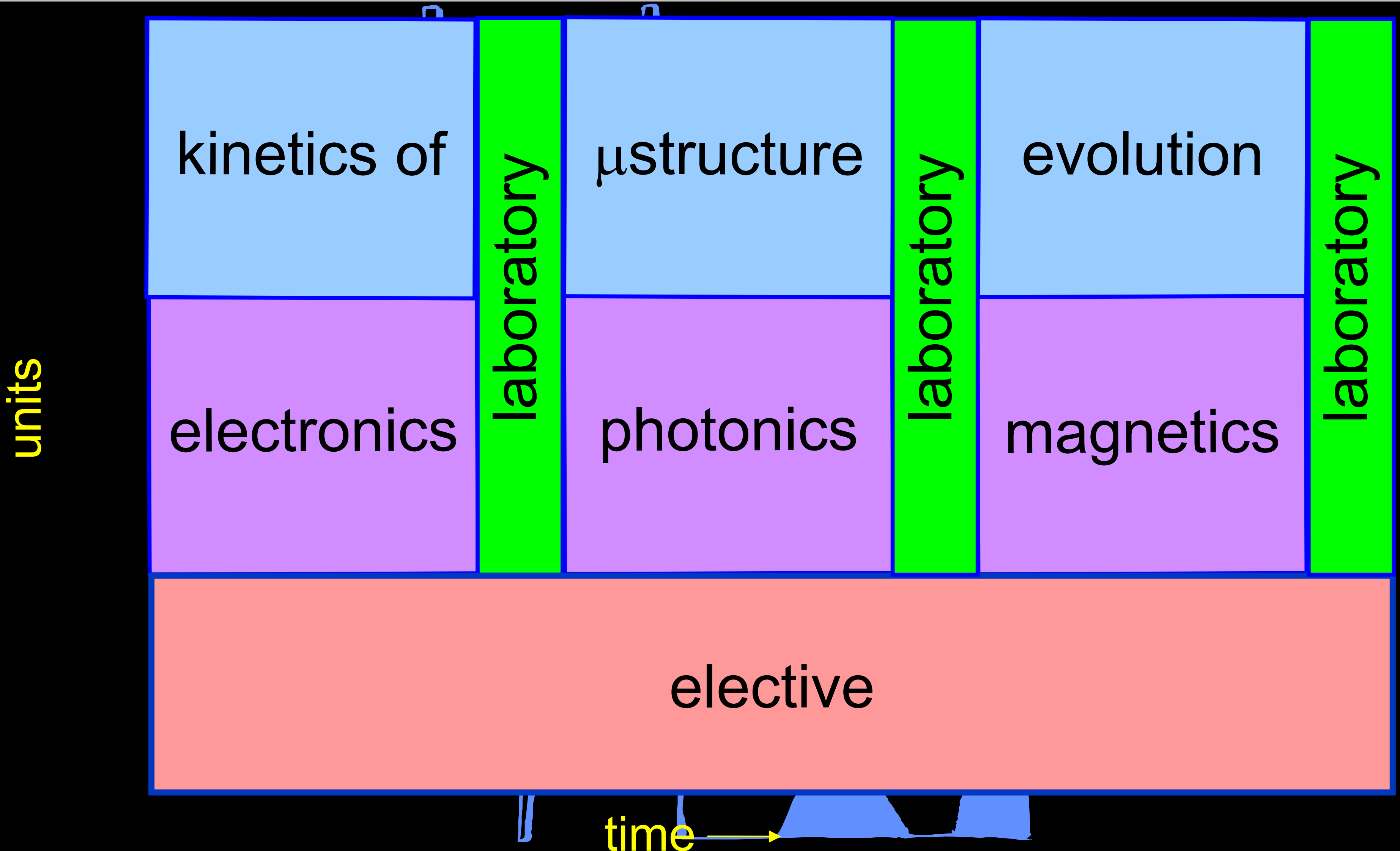
Laboratories

Communcations emphasis:

Report formats

- **memo**
- **journal article**
- **technical report**
- **oral presentation**
- **lab books graded**

Storyboard Spring Year 2



Schedule - Spring Year 2

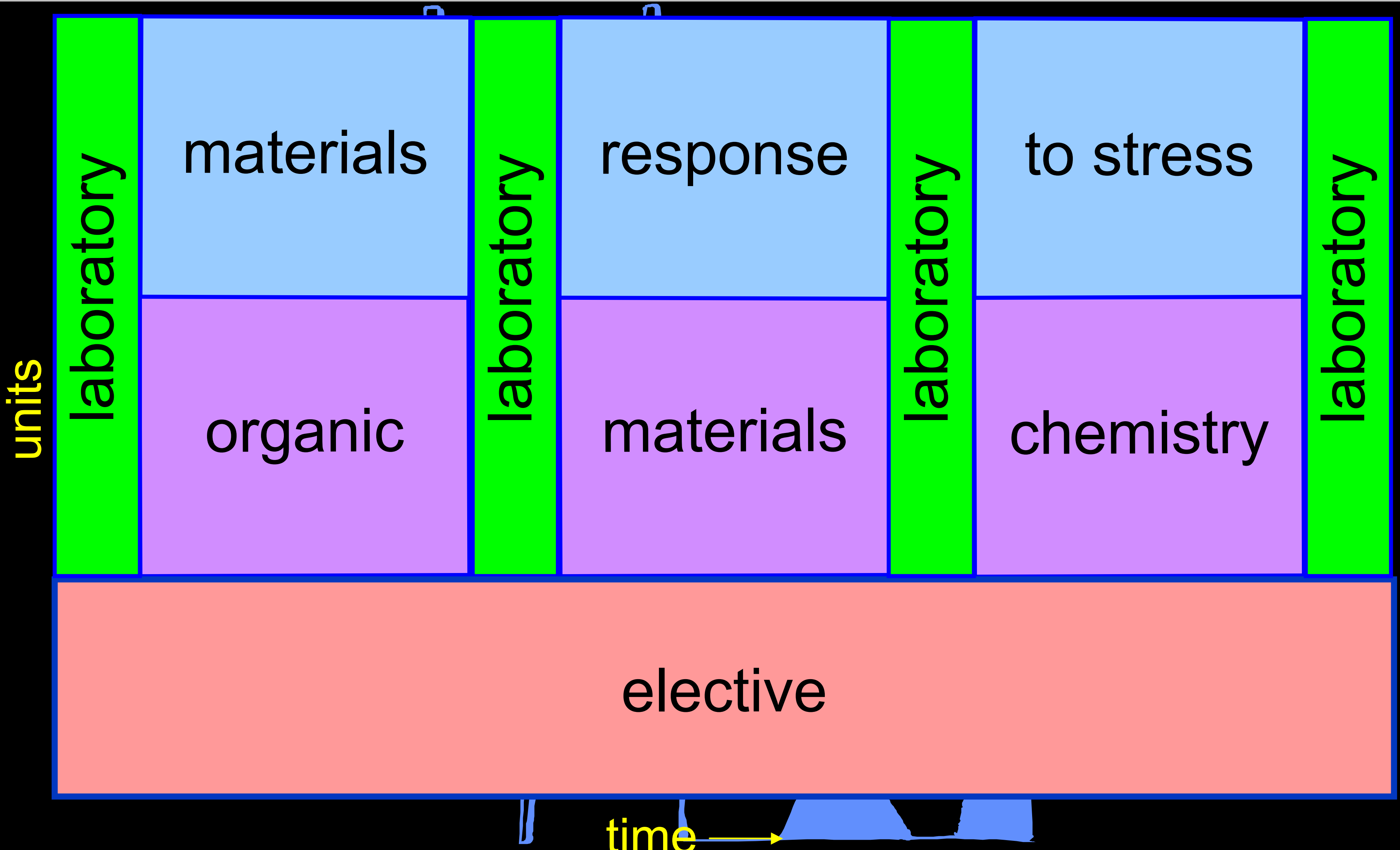
Spring Y2

Feb		4	5	6	7
	10	11	12	13	14
	17	18 (M sch.)	19	20	21
	24	25	26	27	28
March	3	4	5	6	7
	10	11	12	13	14
	17	18	19	20	21
	24	25	26	27	28
April	31	1	2	3	1
	7	8	9	10	11
	14	15	16	17	18
	21	22	23	24	25
May	28	29	30	1	2
	5	6	7	8	9
	12	13	14		

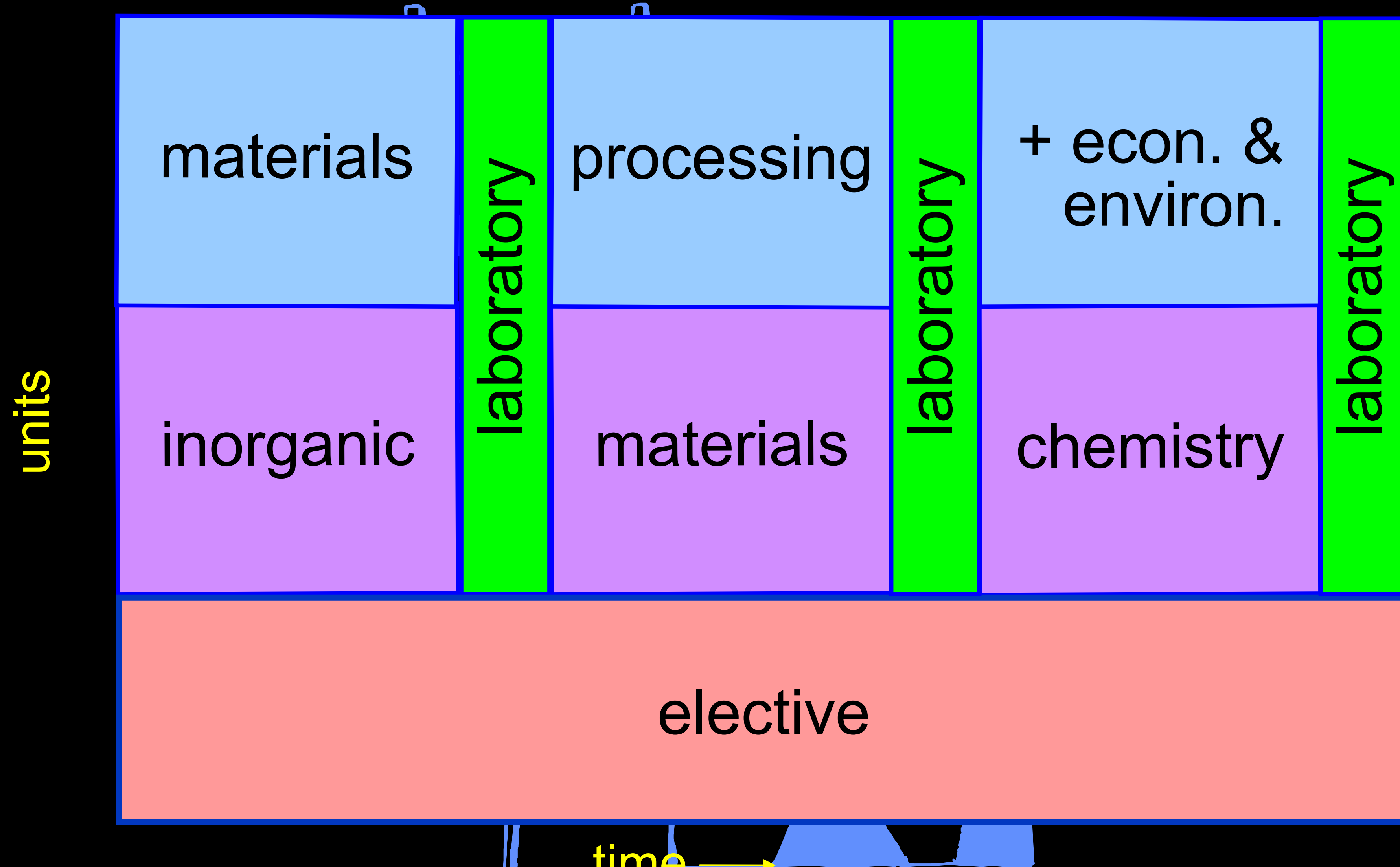
Laboratories (green): Feb 10–14, March 10–14, April 7–11, May 5–9

Vacation (grey): Feb 17, March 24–28, April 21–22

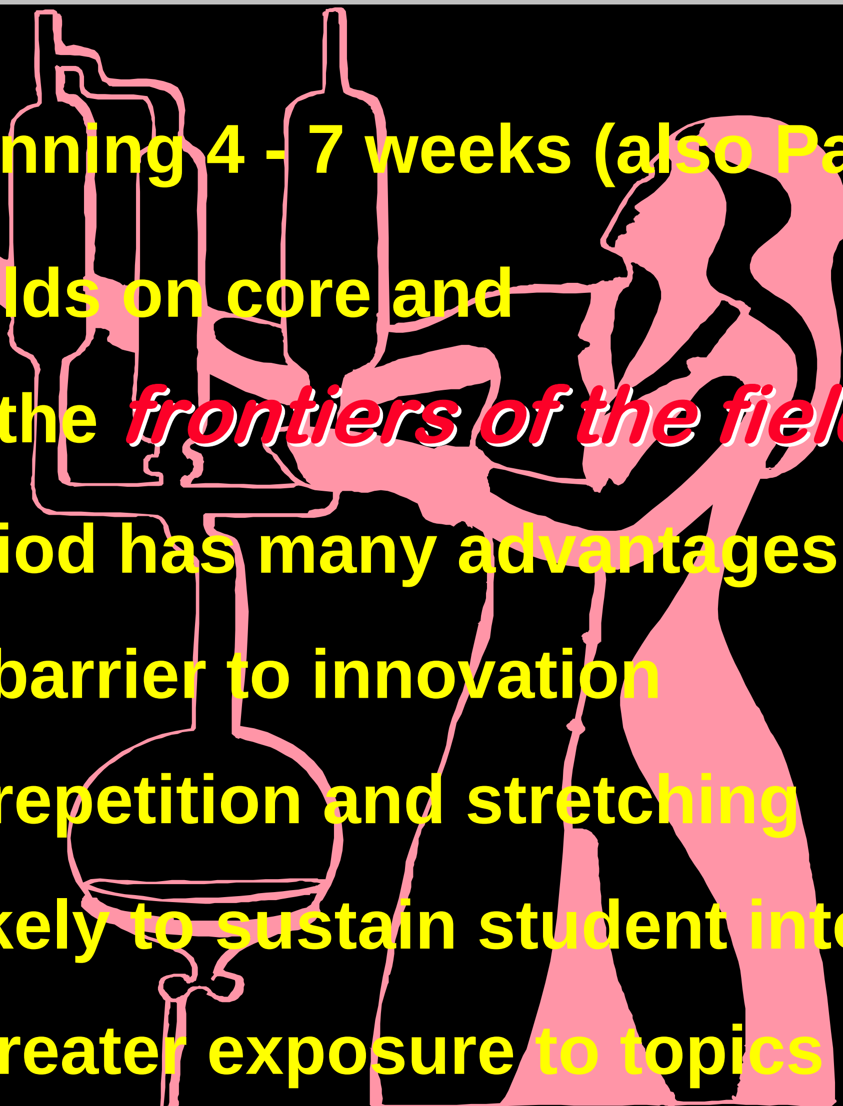
Storyboard Fall Year 3



Storyboard Spring Year 3

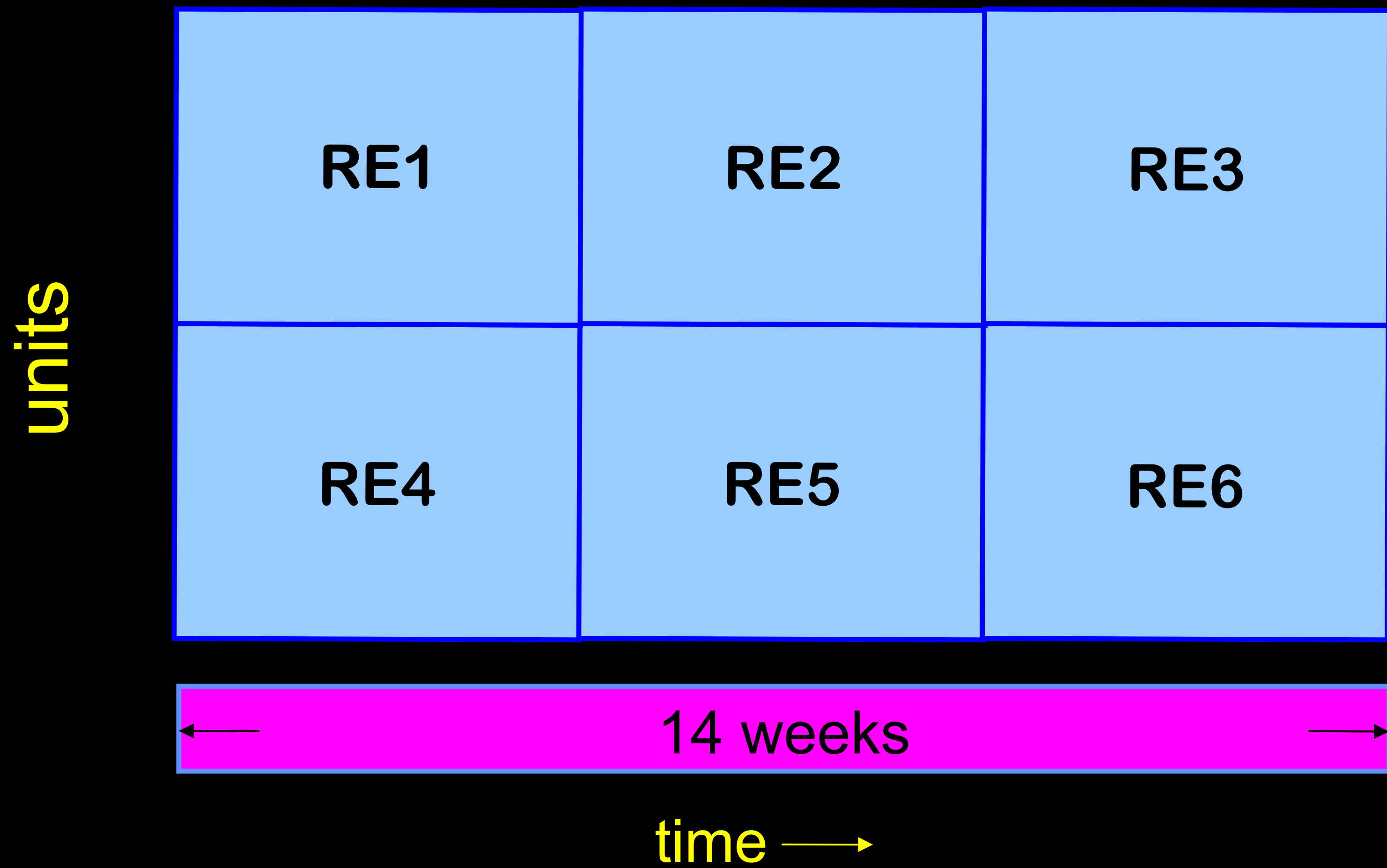


Restricted Electives: “Frontiers of the Field”

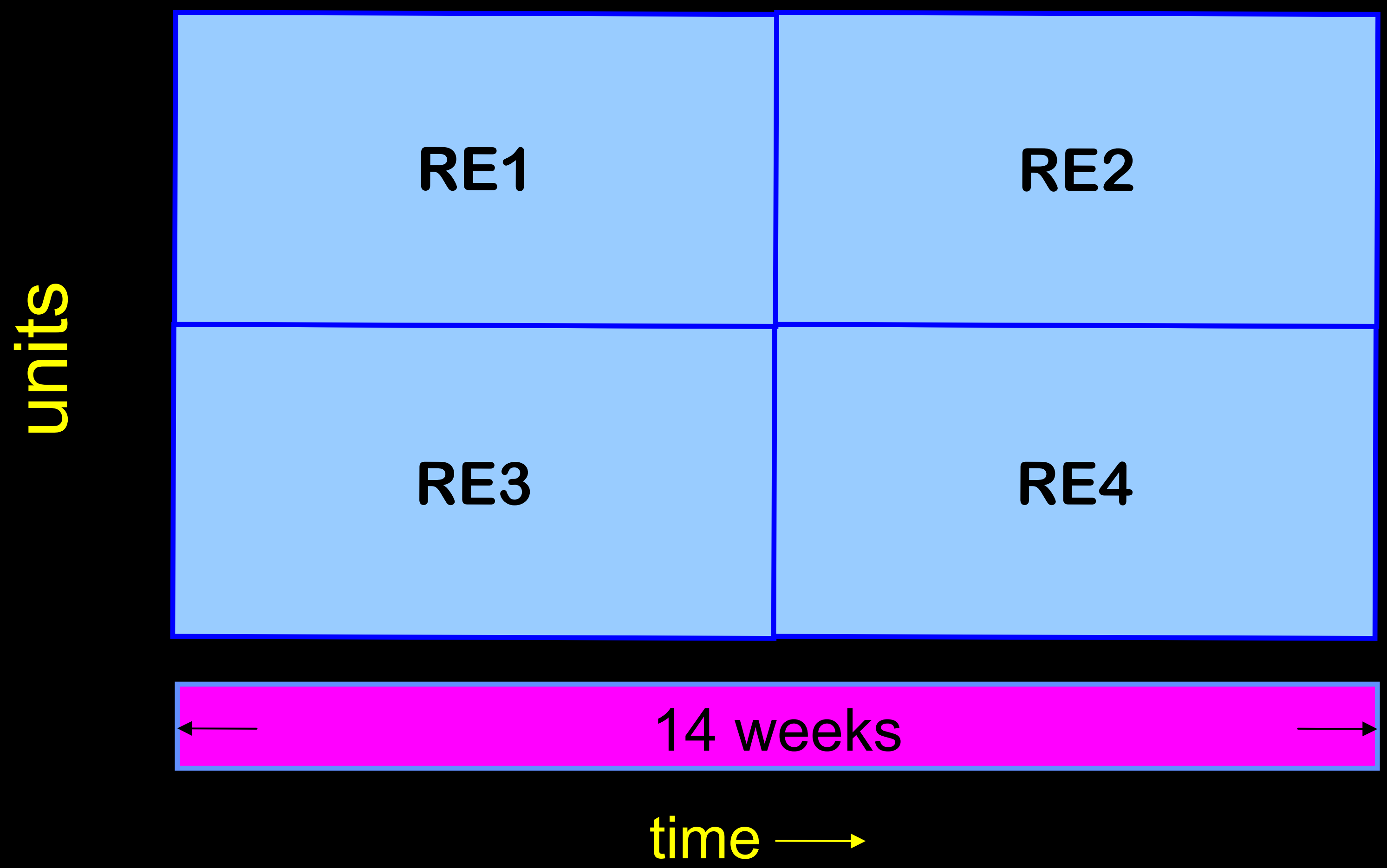


- subjects running 4 - 7 weeks (also Parts 1, 2, etc.)
- content builds on core and moves to the *frontiers of the field*
- shorter period has many advantages:
  1. lowers barrier to innovation
  2. avoids repetition and stretching
  3. more likely to sustain student interest
  4. much greater exposure to topics and faculty

Storyboard - Fall Year 4



Storyboard - Fall Year 4



Storyboard - Spring Year 4

RE7	RE8	RE9

choice of capstone activity:

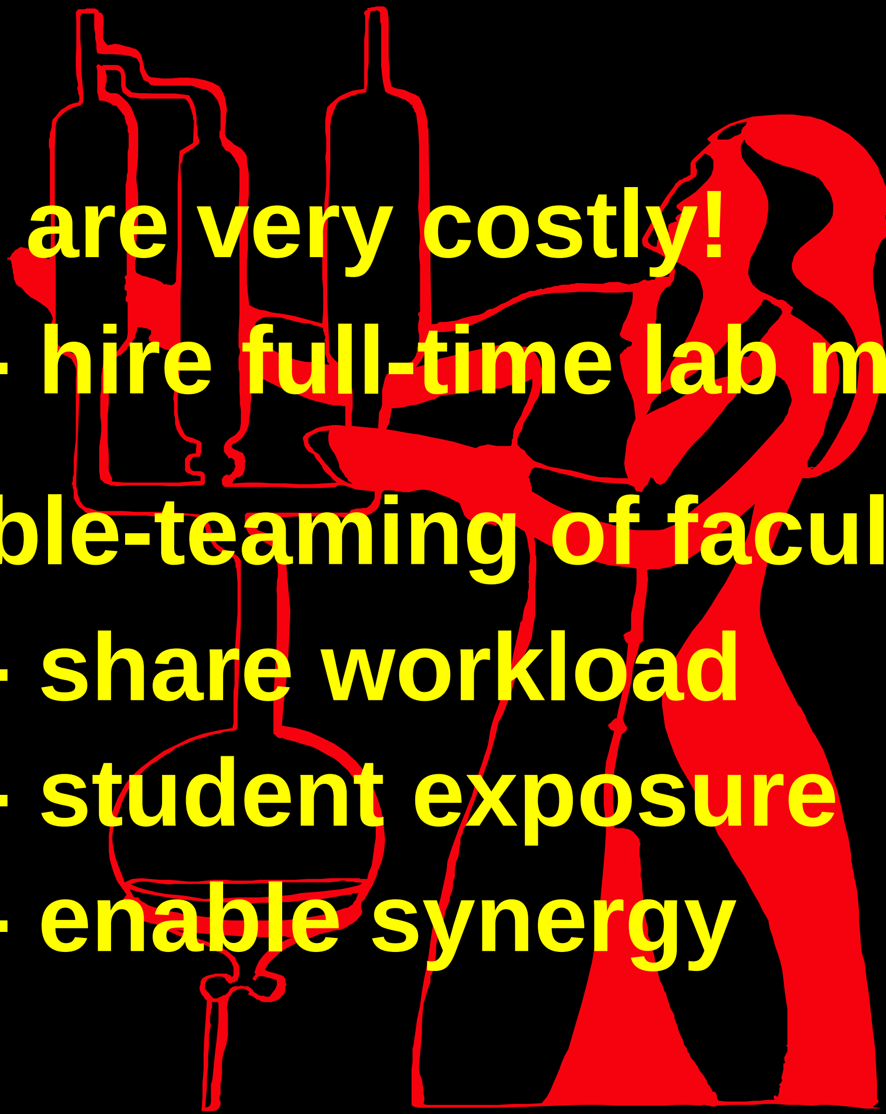
- senior thesis
- industrial internship
- interdisciplinary design studio
- educational design project: new lab module

units

← 14 weeks →

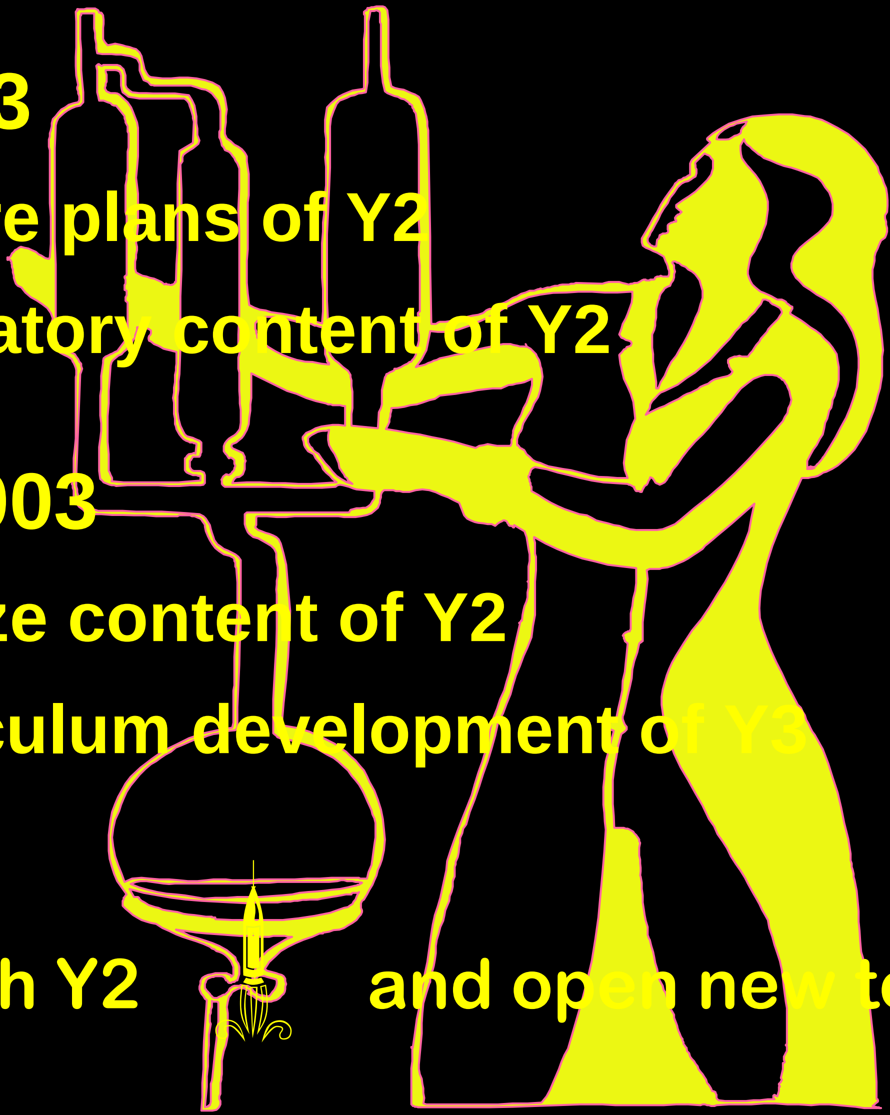
time →

High Resource Intensity



- labs are very costly!
  - hire full-time lab manager
- double-teaming of faculty
  - share workload
  - student exposure
  - enable synergy

Timeline to Fall 2003 Launch



Spring 2003

- lecture plans of Y2
- laboratory content of Y2

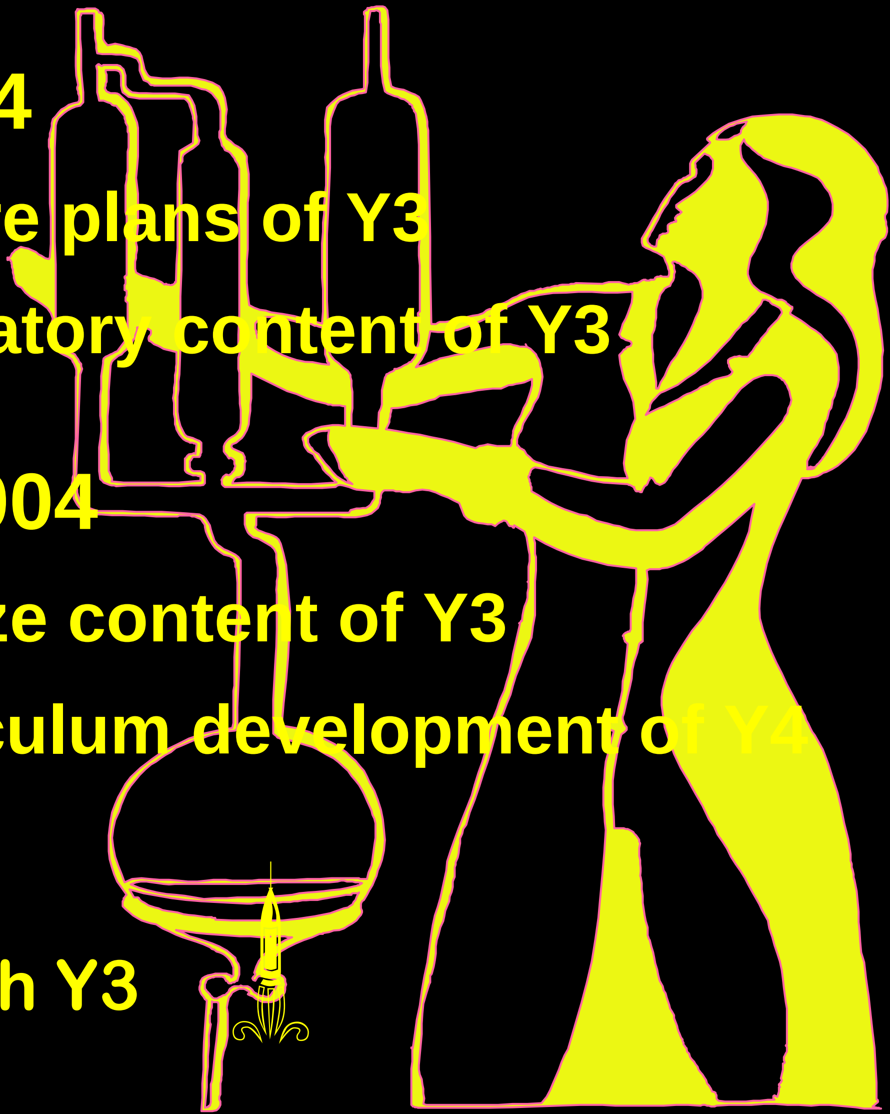
Summer 2003

- finalize content of Y2
- curriculum development of Y3

Fall 2003

- launch Y2 and open new teaching lab

Timeline to Fall 2004 Launch



Spring 2004

- lecture plans of Y3
- laboratory content of Y3

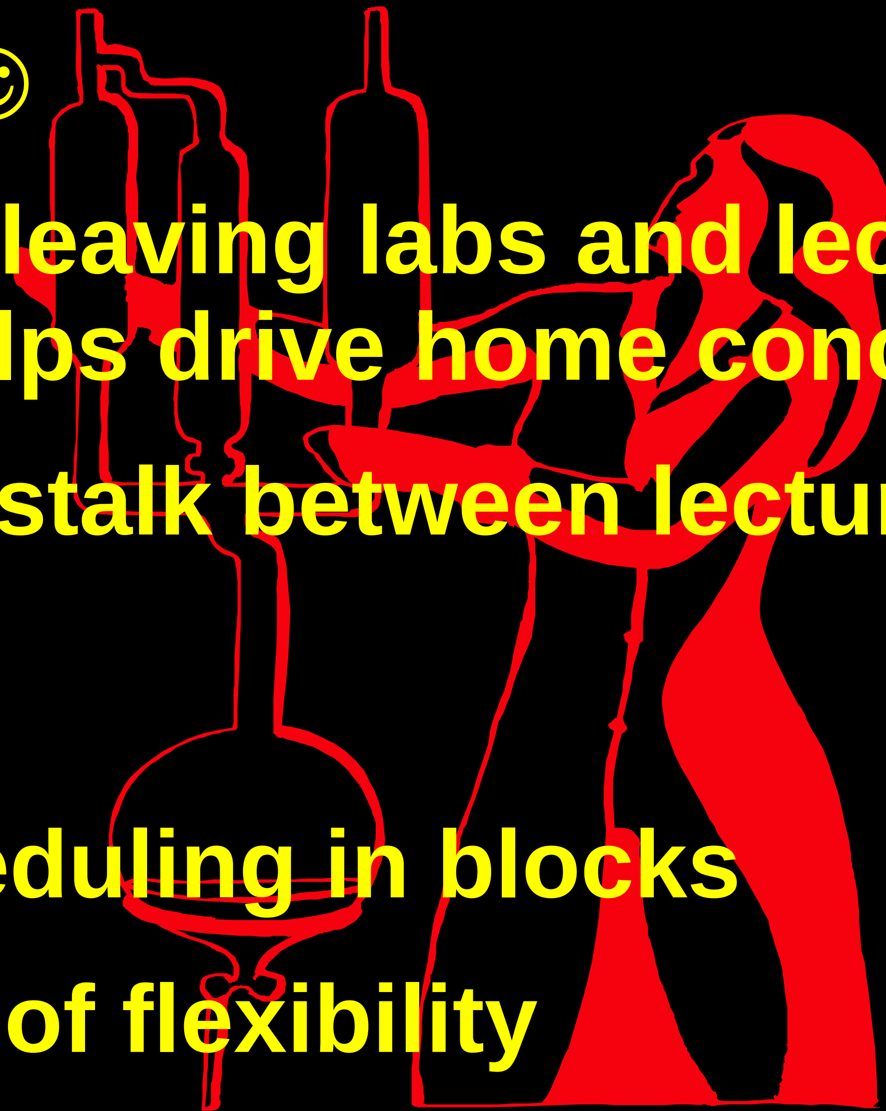
Summer 2004

- finalize content of Y3
- curriculum development of Y4

Fall 2004

- launch Y3

Initial Student Reaction



Good ☺

- ✏ interleaving labs and lectures helps drive home concepts
- ✏ crosstalk between lectures

Bad ☹

- ✏ scheduling in blocks
- ✏ lack of flexibility

What is education?

Education is what remains when you've forgotten all your schooling.

- Benjamin Franklin

A good education

solutions to problems

A better education

methodology
for developing
solutions to problems

A great education

methodology
for developing
methodologies

...in the final analysis

- today's students need to be engaged if they are to learn ☞ **context**
- engineering schools need to learn to value curriculum development as they value research accomplishments

  ☞ **new performance metrics**
- University of Tokyo + MIT together can play a role in shaping curriculum

  ☞ **partnerships**

Our mission: