RC22767 (W0304-077) April 9, 2003
Electrical Engineering

IBM Research Report

The Physics of Computer Components

Mary Y. Wisniewski
IBM Research Division
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, NY 10598

Richard N. Louie
Department of Physics
Pacific Lutheran University
1010 122nd Street South
Tacoma, WA 98447

Abstract

Thank you to Chairman Kiko Galvez and thank you to Savi Iyer for inviting me to present this talk. I'd like to talk a bit about why we wrote this talk.

Six years ago Richard Louie and I were graduate students at Cornell University, studying experimental physics, and prior to that we were undergraduates at Harvard University. Richard's area of expertise is in low temperature and solid state, and my background is in optical phase conjugation and electron microscopy. After receiving our Ph.D.'s, I took a position as a Research Staff Member in a different area - electrical engineering in the design department at IBM Research, where I design computer hardware with computer-aided design tools, and Richard took a position in academia as an assistant professor in the Physics Department at PLU. At IBM, doing my design projects, I was struck by how relevant the physics we had learned as undergraduates and graduates was to my current work, and that seeing engineering problems from a physics perspective might benefit high school students and undergraduates. For his part, Richard invited me to PLU in 1998 to discuss "Post-baccalaureate choices and career paths in physics and engineering" to give his physics undergraduates some perspective on their options. This presentation has evolved into our presentation today, "The Physics of Computer Components" which we have been working on since that time, and it is our hope to use a few simple examples of computer components to illustrate that on the one hand, to students of physics, engineering basics and knowledge of design constraints are useful in design, and on the other hand, to students of engineering, that physics basics are relevant for their designs (See Figure 1).

Index Terms

computer components.

I. ACKNOWLEDGMENTS

I thank Izzy Bendrihem for taking apart my IBM Thinkpad T23 so that we were able to take the photographs of the components shown in this talk, my colleagues Giovanni, Maurice, Tom, and Cev for discussions, Tom Way at IBM Communications for permission to use images from the IBM photo gallery in this talk, and Rob and Asya for the wafers that I will be showing as demos (see Figure 2).

II. OUTLINE

The structure of this talk is as follows. First I will motivate why we have taken care to think about this subject, next I will discuss applications to computer components, which will be the majority of the talk, then I will briefly discuss the impact that physicists have and some diagnostic techniques that are currently used at IBM, then a bit of history to provide perspective on the inventions and discoveries involved in computer components, and finally I will conclude and show our references (see Figure 3).

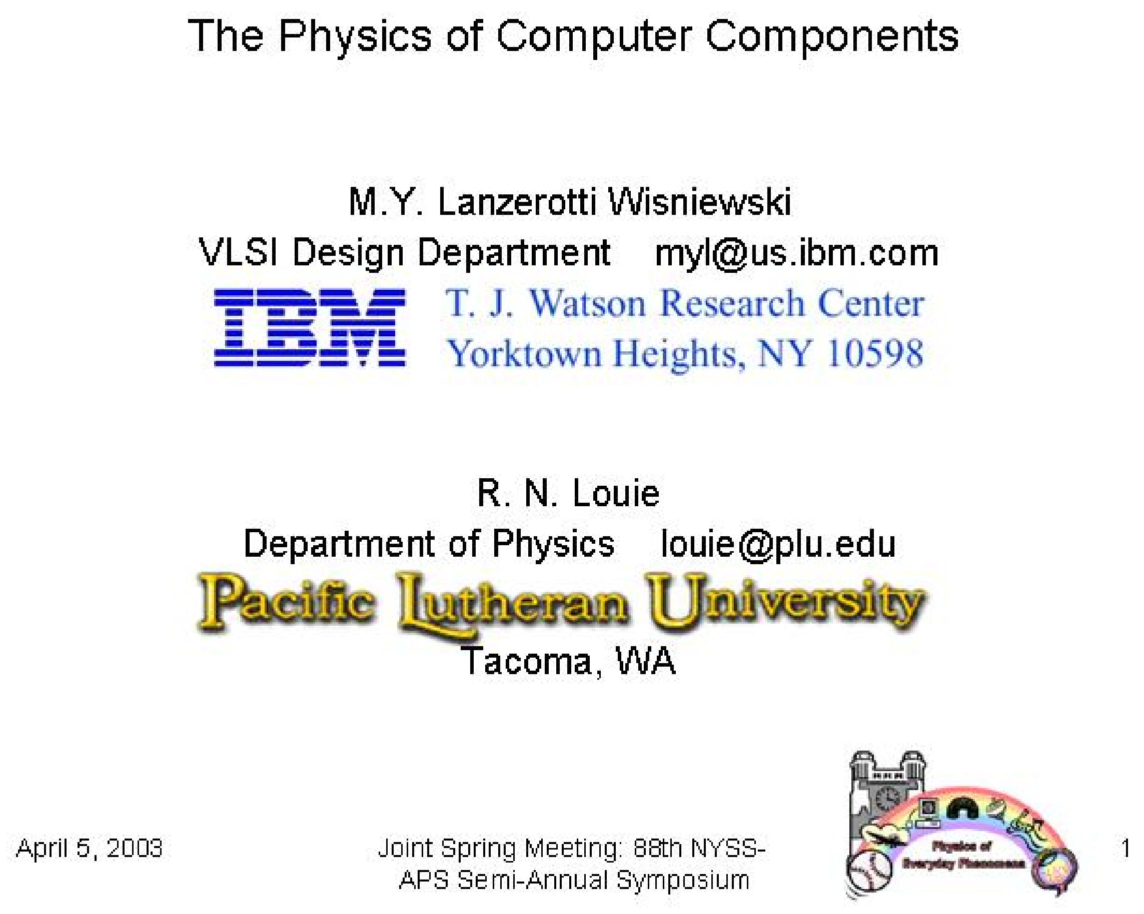
III. MOTIVATION.

With the rapid advancement in technology, particularly with respect to computer hardware, young people are using new and novel devices that didn't exist even 15 years ago, when we were in college. So the question we want to ask to start this talk is, can we teach physics students that an understanding of engineering design constraints is useful in designs and to also teach engineering students that an understanding of physics is relevant to better design (see Figure 4)?

The environment in which we ask this question is one in which some academic institutions are currently re-evaluating the content of an undergraduate education. For our part, we believe that our talk will provide some guidance in pointing to one approach that will help educate twenty-first century physicists and twenty-first century engineers (see Figure 5).

At the same time we ask ourselves and our students the two questions: Why? and What if? - For example, Why is this material useful? Why am I doing this? and What if I make this and so modification? (see Figure 6).

The structure of this talk is provided by a typical undergraduate physics curriculum, and we have mapped one components of a typical computer to each topic or class, as shown in this table (see Figure 7), although as we will see, to understand the operation of most components requires a multi-disciplinary knowledge base. For each topic we have time to discuss only a few simple concepts.



The Physics of Computer Components

M.Y. Lanzerotti Wisniewski
VLSI Design Department myl@us.ibm.com
IBM T. J. Watson Research Center
Yorktown Heights, NY 10598

R. N. Louie
Department of Physics louie@plu.edu
Pacific Lutheran University
Tacoma, WA

April 5, 2003 Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium 1

Fig. 1. Title page: The Physics of Computer Components.

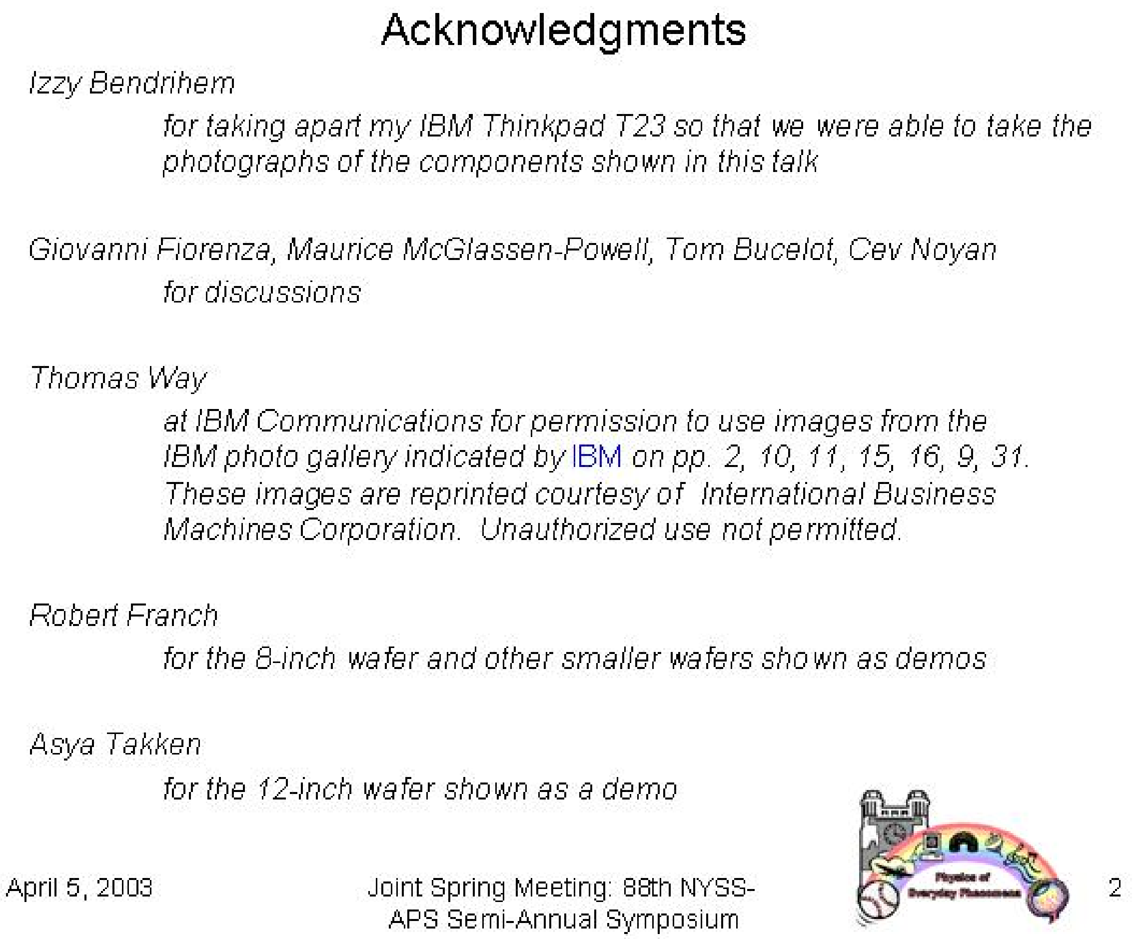
So, for example, to illustrate a few concepts in mechanics, we choose the keyboard, for electricity and magnetism we choose wires, a capacitor, and a transistor, for optics we choose the flat panel display, for laser physics the DVD player, for solid state physics the hard disk drive, and we do so at a level where expanded to perhaps one semester, typical high school or college students can be exposed to useful concepts in disciplines that normally span two to three years or more. Finally, I discuss quantum mechanics very briefly although there are some possible examples that we hope to include in our future work.

The keyboard and flat panel display are examples of computer I/O or input/outputs, the transistors and wires perform the computations and the capacitor, DVD player, and hard disk provide places to store the results of our computations. Working within various design constraints, different companies create these components and push the limits of the technology to bring us hardware that's faster, smaller, less power hungry, and has greater storage density than the previous components (see Figure 8).

IV. MECHANICS: KEYBOARD

Let's start with design constraints for the keyboard. Each key location (QWERTY) and home row configuration even on modern computers is inherited from the arrangment chosen in 1872 to prevent jamming of mechanical typewriters. Each key size is also approximately the size of a finger tip (see Figure 9).

Additional design constraints are set by the American National Standards Institute. They set the key-to-key spacing and vertical displacement as well as maximum force of 1.5 Newtons. Within these constraints,



Acknowledgments

Izzy Bendrihem

for taking apart my IBM Thinkpad T23 so that we were able to take the photographs of the components shown in this talk

Giovanni Fiorenza, Maurice McGlassen-Powell, Tom Bucelot, Cev Noyan

for discussions

Thomas Way

at IBM Communications for permission to use images from the IBM photo gallery indicated by IBM on pp. 2, 10, 11, 15, 16, 9, 31. These images are reprinted courtesy of International Business Machines Corporation. Unauthorized use not permitted.

Robert Franch

for the 8-inch wafer and other smaller wafers shown as demos

Asya Takken

for the 12-inch wafer shown as a demo

April 5, 2003 Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium 2

Fig. 2. Acknowledgments.

the design of the curve $F(x)$ is not simply $-k \times x$ but has the behavior shown in this graph, where the glitch is feedback to the typist that the key has been depressed. Also, less force is required for expert typists, hence we have soft touch keyboards (see Figure 10).

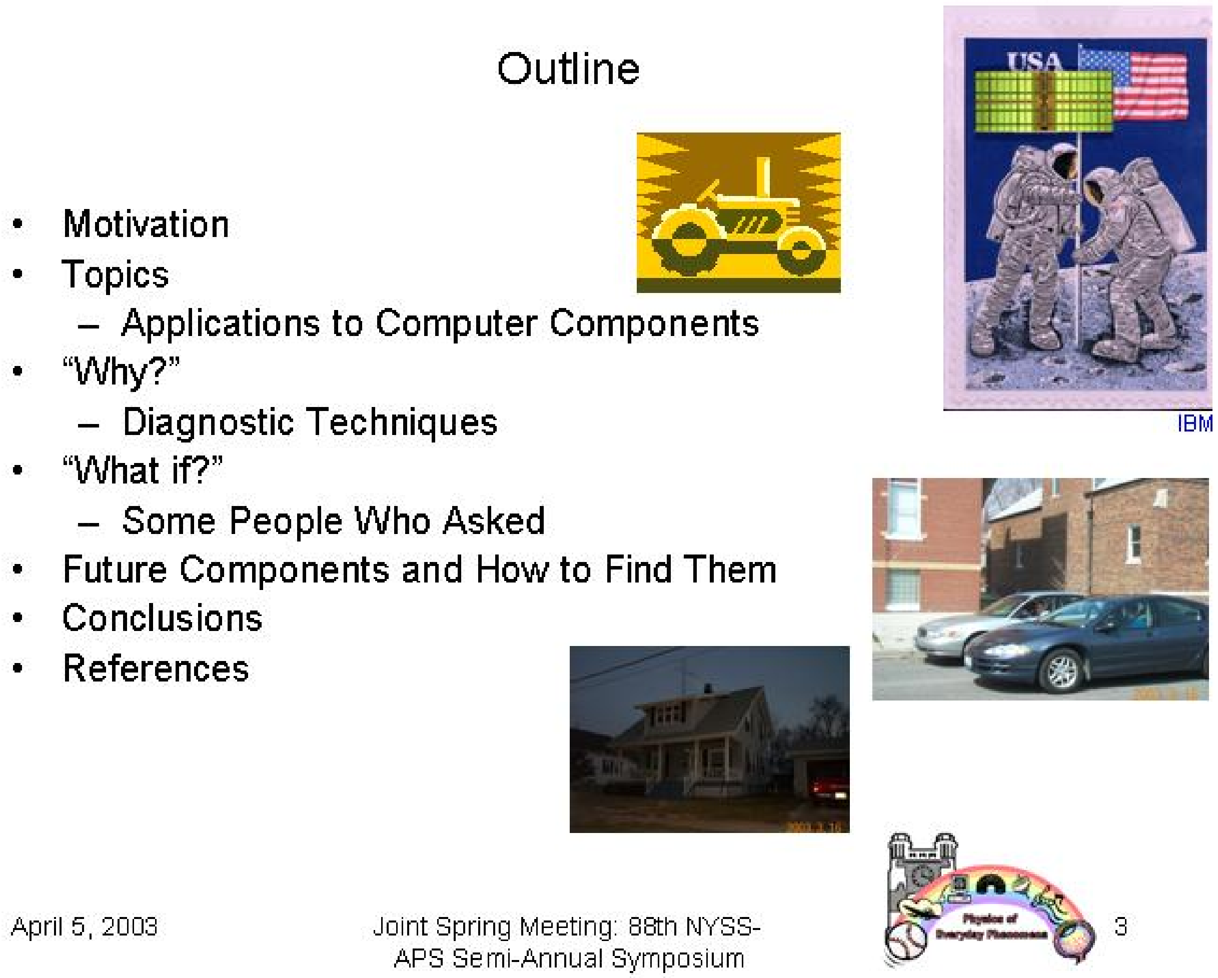
Carpal tunnel syndrome didn't exist in the old days because word processing was far less easy - our movements are repetitive because we don't have to advance the paper, thread new paper, et cetera - we just type and type and type!

V. OVERVIEW OF COMPUTERS

Computers are designed to carry out instructions at a rate of 10^8 instructions per second and to store the results for use in future instructions in memory that can store on the order of 10^8 bits. This process is carried out by the main components of the computer - the CPU (central processing unit), cache and main memory. The instructions are executed by a microprocessor that contains the CPU and cache. The results can be stored for future use in the cache or in main memory.

In this section of the talk I will discuss the physics of the building blocks of the CPU and main memory, namely wires, capacitors, and transistors.

This foil (see Figure 11) shows an example of a POWER4 chip, in which I was responsible for wiring the Instruction Fetch Unit. The chips are fabricated on 8-inch ($200mm$) silicon wafers, and there are approximately 50 chips per wafer. The image below shows a packaged chip. The chip is approximately $2cm \times 2cm$



Outline

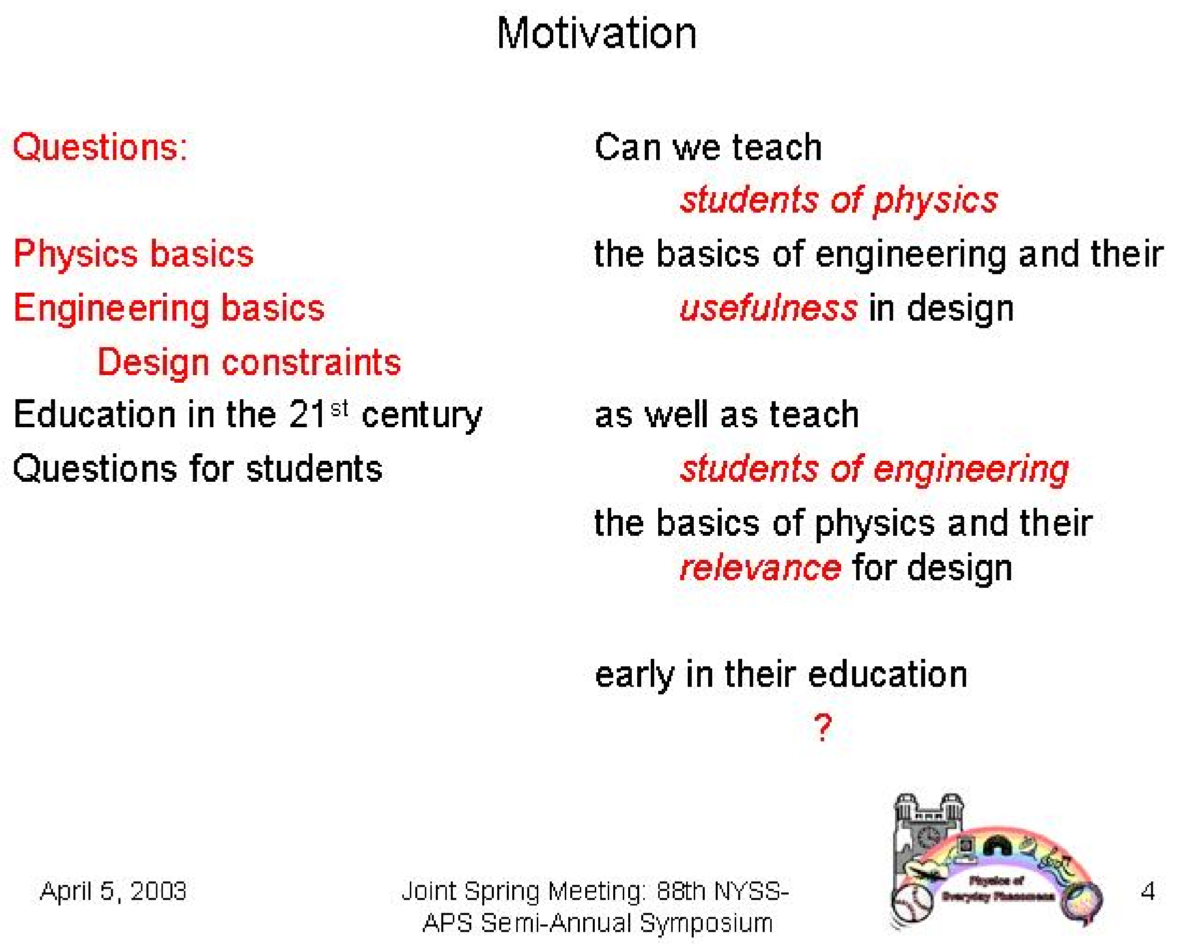
- Motivation
- Topics
  - – Applications to Computer Components
- "Why?"
  - – Diagnostic Techniques
- "What if?"
  - – Some People Who Asked
- Future Components and How to Find Them
- Conclusions
- References

April 5, 2003 Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium 3

Fig. 3. Outline of the Physics of Computer Components.

(400 square millimeters) and is shown to scale on this stack of copper pennies. If we zoom in we see a top view and cross-sectional view of copper wires which carry signals among the transistors. There are over 170 million transistors, 1 mile of copper wires operating at 1.3 GHz in eight layers of metal in a silicon area the size slightly larger than the size of a copper penny (see Figure 12).

At IBM a $300mm$ fab was constructed last year to start fabricating chips on $300mm$ $(12 - inch)$ wafers, so I'll now pass out examples of these wafers - $8 - inch$, $12 - inch$, and much older wafers, as well as an example of a POWER4 chip.



Motivation

Questions:

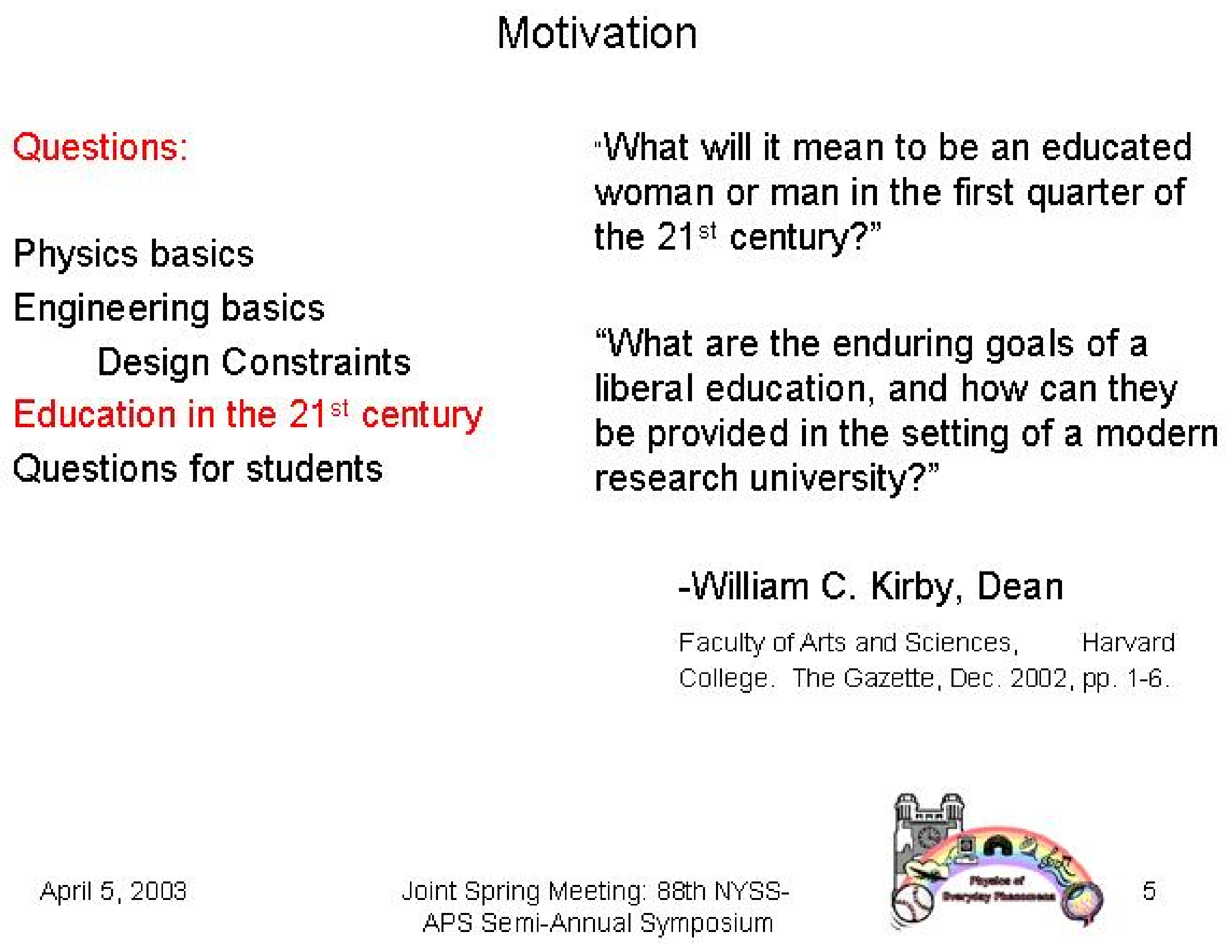
Physics basics
Engineering basics
  Design constraints
Education in the 21st century
Questions for students

Can we teach
  students of physics
the basics of engineering and their
  usefulness in design

as well as teach
  students of engineering
the basics of physics and their
  relevance for design

early in their education
?

Fig. 4. Motivation: Questions about physics basics and engineering basics.



Motivation

Questions:

Physics basics
Engineering basics
    Design Constraints
Education in the 21st century
Questions for students

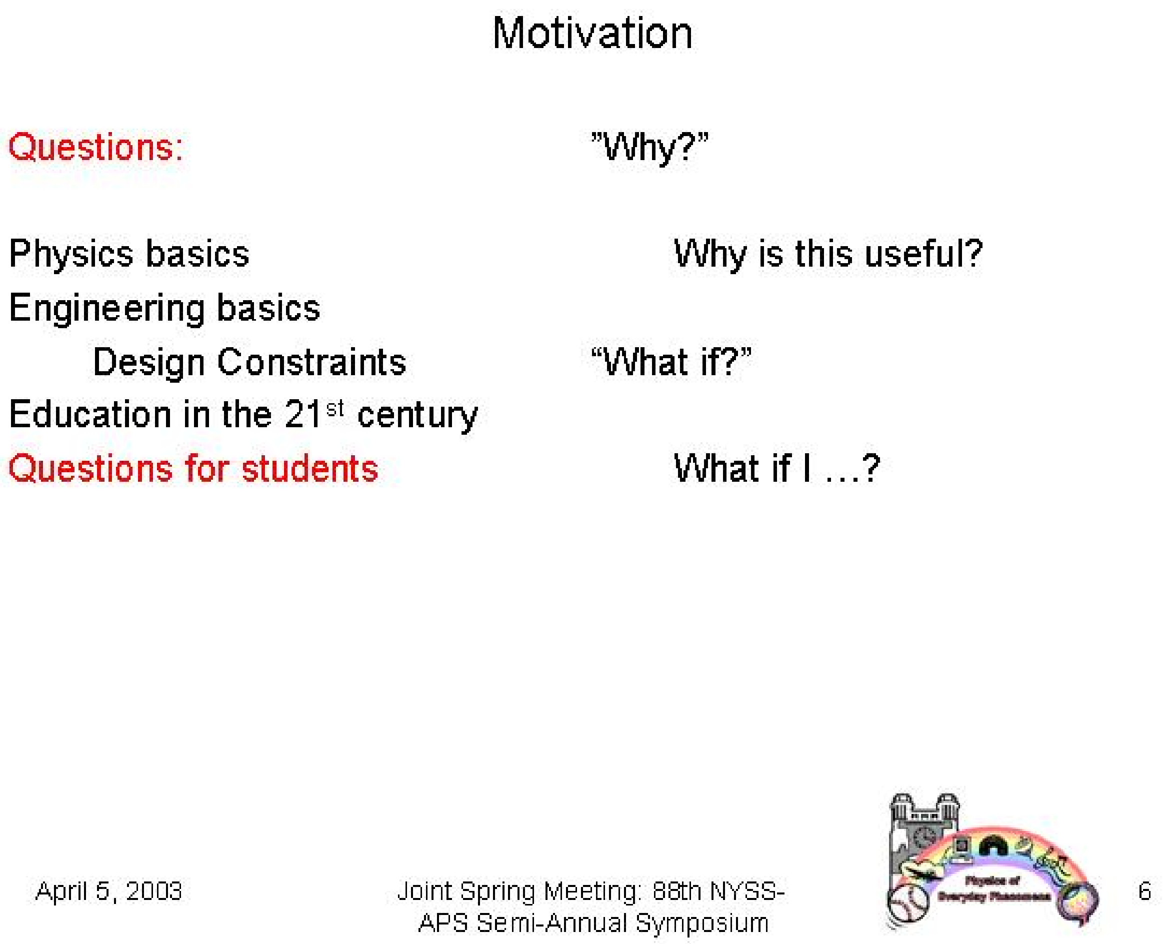
"What will it mean to be an educated woman or man in the first quarter of the 21st century?"

"What are the enduring goals of a liberal education, and how can they be provided in the setting of a modern research university?"

-William C. Kirby, Dean

Faculty of Arts and Sciences, Harvard College. The Gazette, Dec. 2002, pp. 1-6.

Fig. 5. Motivation: Questions about education in the 21st century.



Motivation

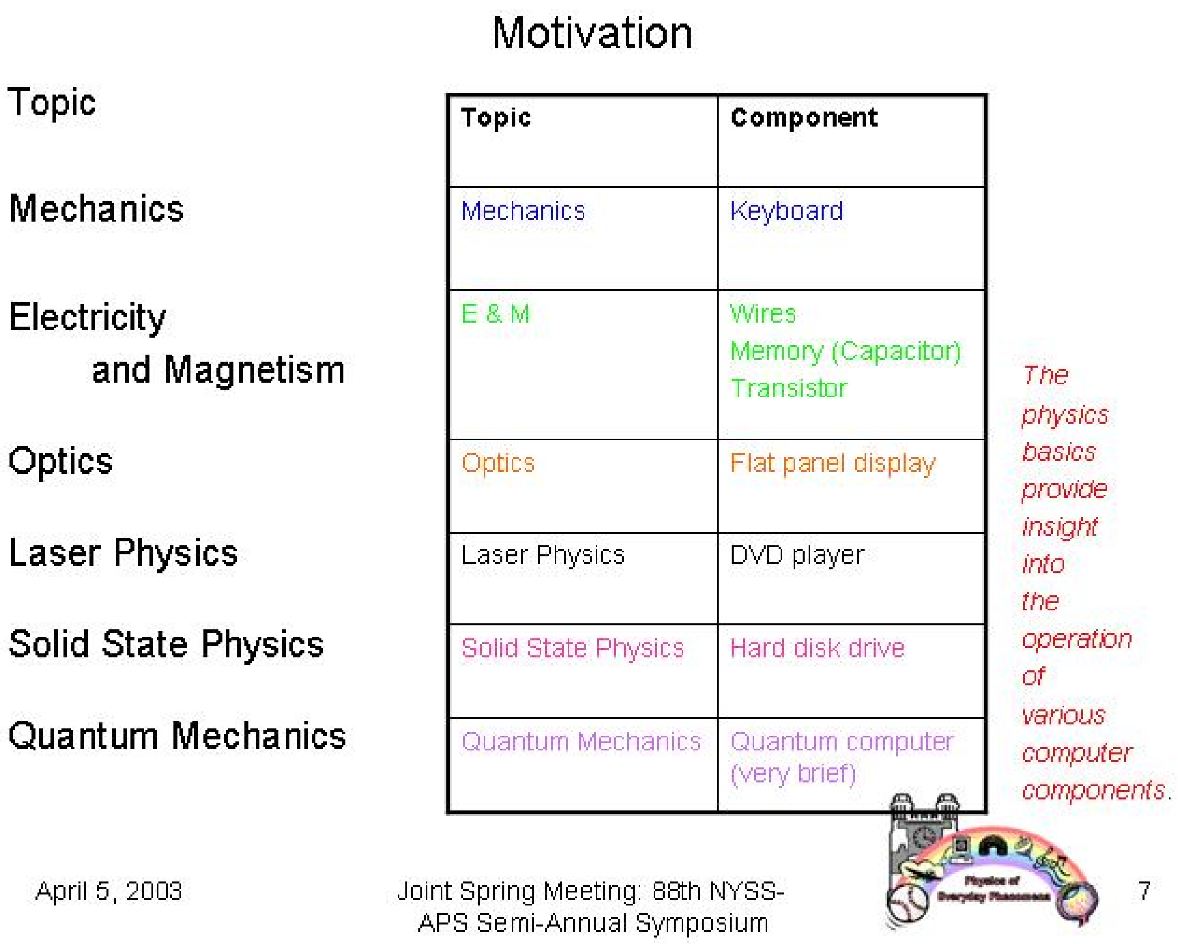
Questions:	”Why?”
Physics basics	Why is this useful?
Engineering basics	
Design Constraints	“What if?”
Education in the 21^{st} century	
Questions for students	What if I …?

April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

Physics of Everyday Phenomena

Fig. 6. Motivation: Questions for students.



Motivation

Topic

Mechanics

Electricity
and Magnetism

Optics

Laser Physics

Solid State Physics

Quantum Mechanics

Topic	**Component**
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

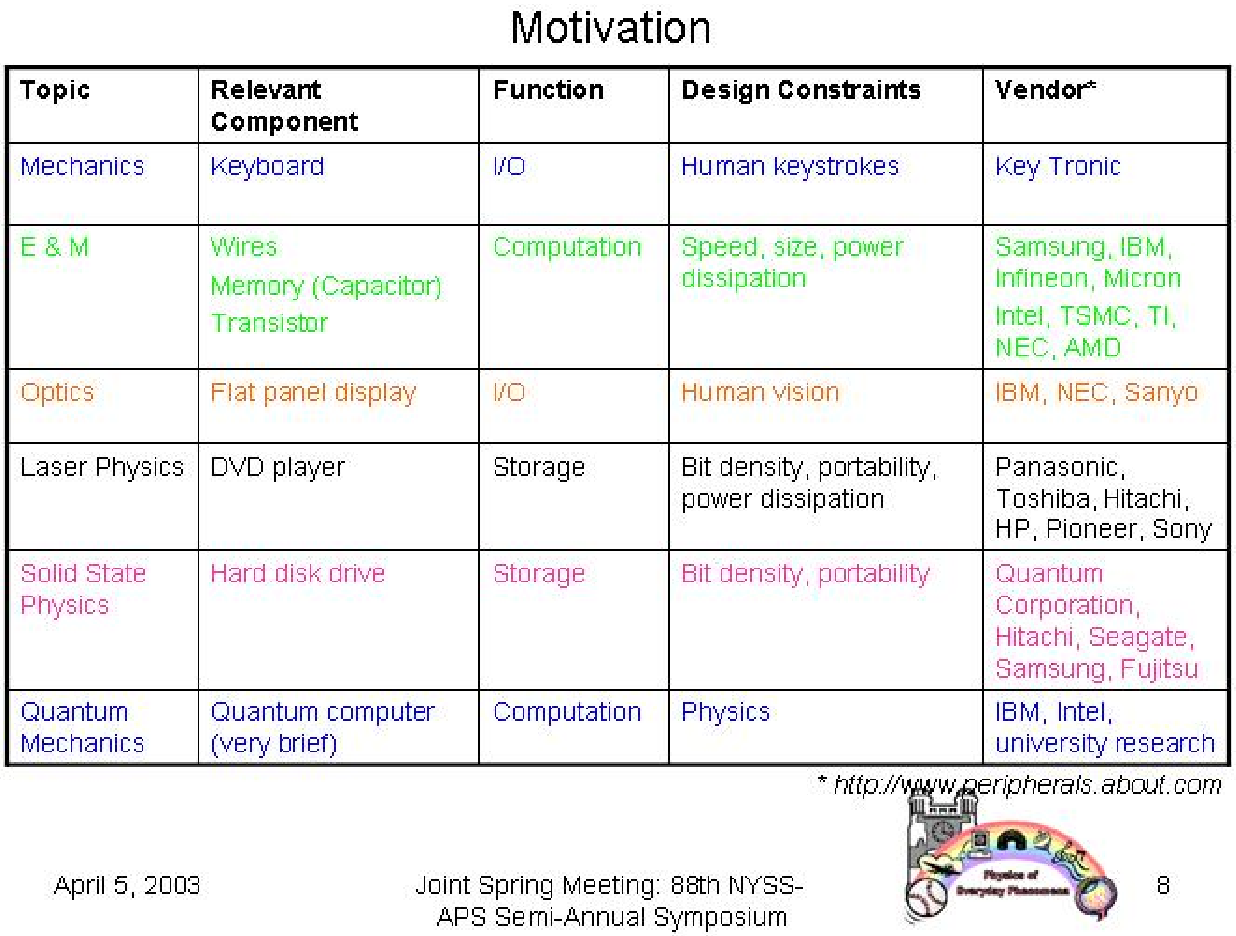
The physics basics provide insight into the operation of various computer components.

April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

7

Fig. 7. Motivation: Topics and a computer component for each.



Motivation

Topic	Relevant Component	Function	Design Constraints	Vendor*
Mechanics	Keyboard	I/O	Human keystrokes	Key Tronic
E & M	Wires Memory (Capacitor) Transistor	Computation	Speed, size, power dissipation	Samsung, IBM, Infineon, Micron Intel, TSMC, TI, NEC, AMD
Optics	Flat panel display	I/O	Human vision	IBM, NEC, Sanyo
Laser Physics	DVD player	Storage	Bit density, portability, power dissipation	Panasonic, Toshiba, Hitachi, HP, Pioneer, Sony
Solid State Physics	Hard disk drive	Storage	Bit density, portability	Quantum Corporation, Hitachi, Seagate, Samsung, Fujitsu
Quantum Mechanics	Quantum computer (very brief)	Computation	Physics	IBM, Intel, university research

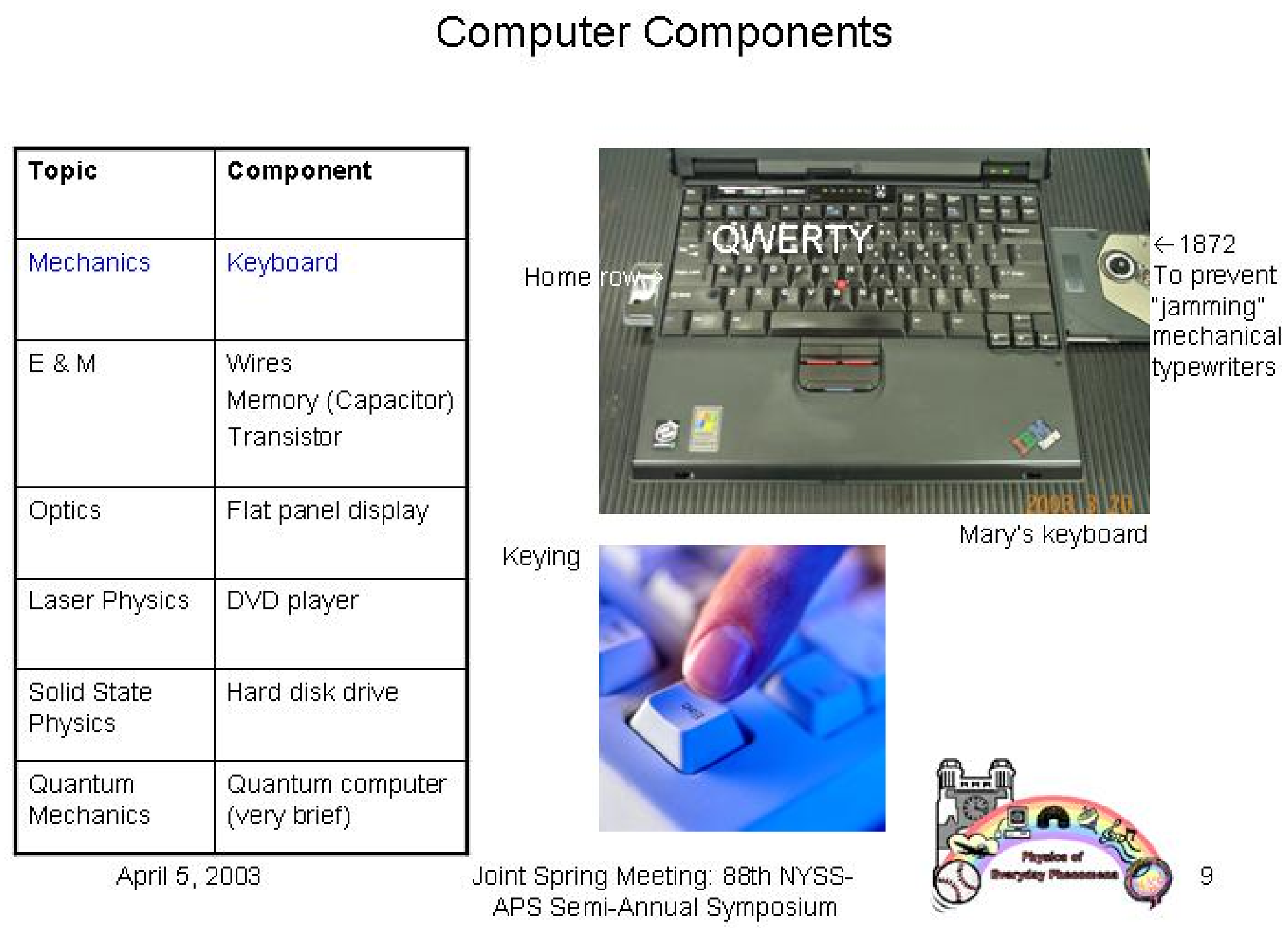
* http://www.peripherals.about.com

April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

8

Fig. 8. Motivation: Function, Design Constraints, and Vendors of Computer Components.



Computer Components

Topic	**Component**
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Home row→

QWERTY

←1872
To prevent
"jamming"
mechanical
typewriters

Mary's keyboard

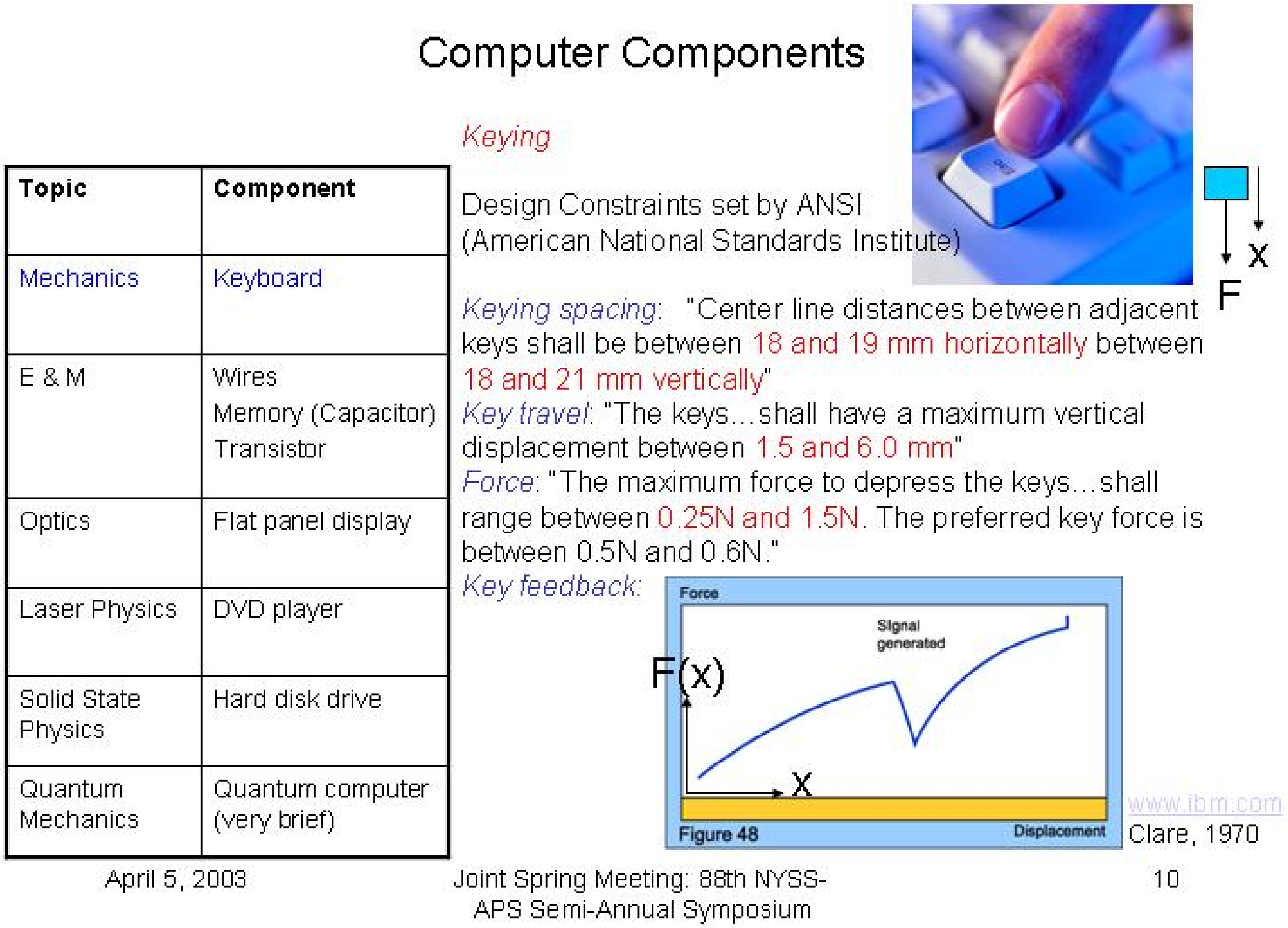
Keying

April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

9

Fig. 9. Mechanics: Keyboard.



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Keying

Design Constraints set by ANSI (American National Standards Institute)

Keying spacing: "Center line distances between adjacent keys shall be between 18 and 19 mm horizontally between 18 and 21 mm vertically"

Key travel: "The keys…shall have a maximum vertical displacement between 1.5 and 6.0 mm"

Force: "The maximum force to depress the keys…shall range between 0.25N and 1.5N. The preferred key force is between 0.5N and 0.6N."

Key feedback:

www.ibm.com

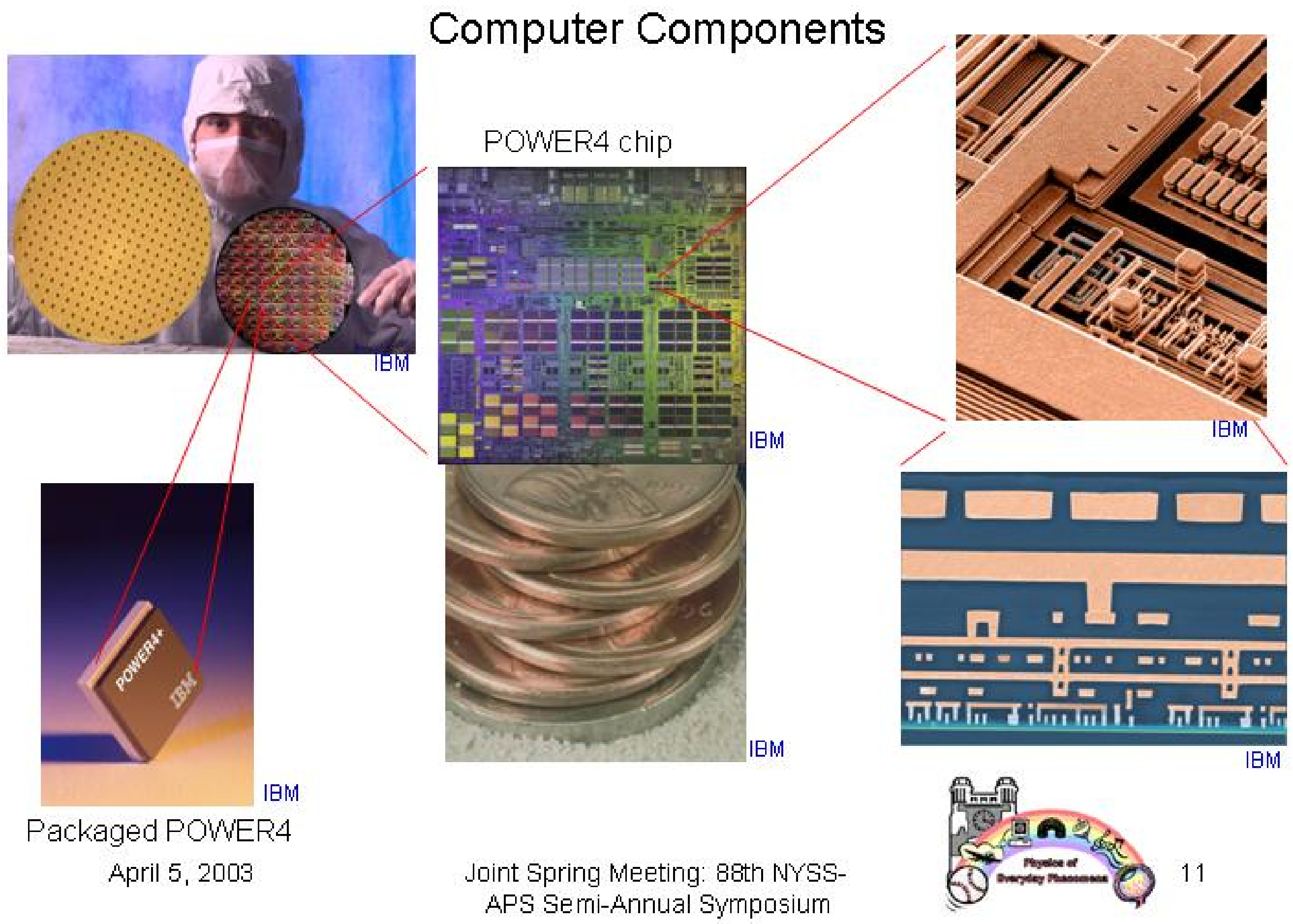
Clare, 1970

April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

10

Fig. 10. Mechanics: Keyboard (continued).



Computer Components

POWER4 chip

IBM

IBM

IBM

IBM

IBM

IBM

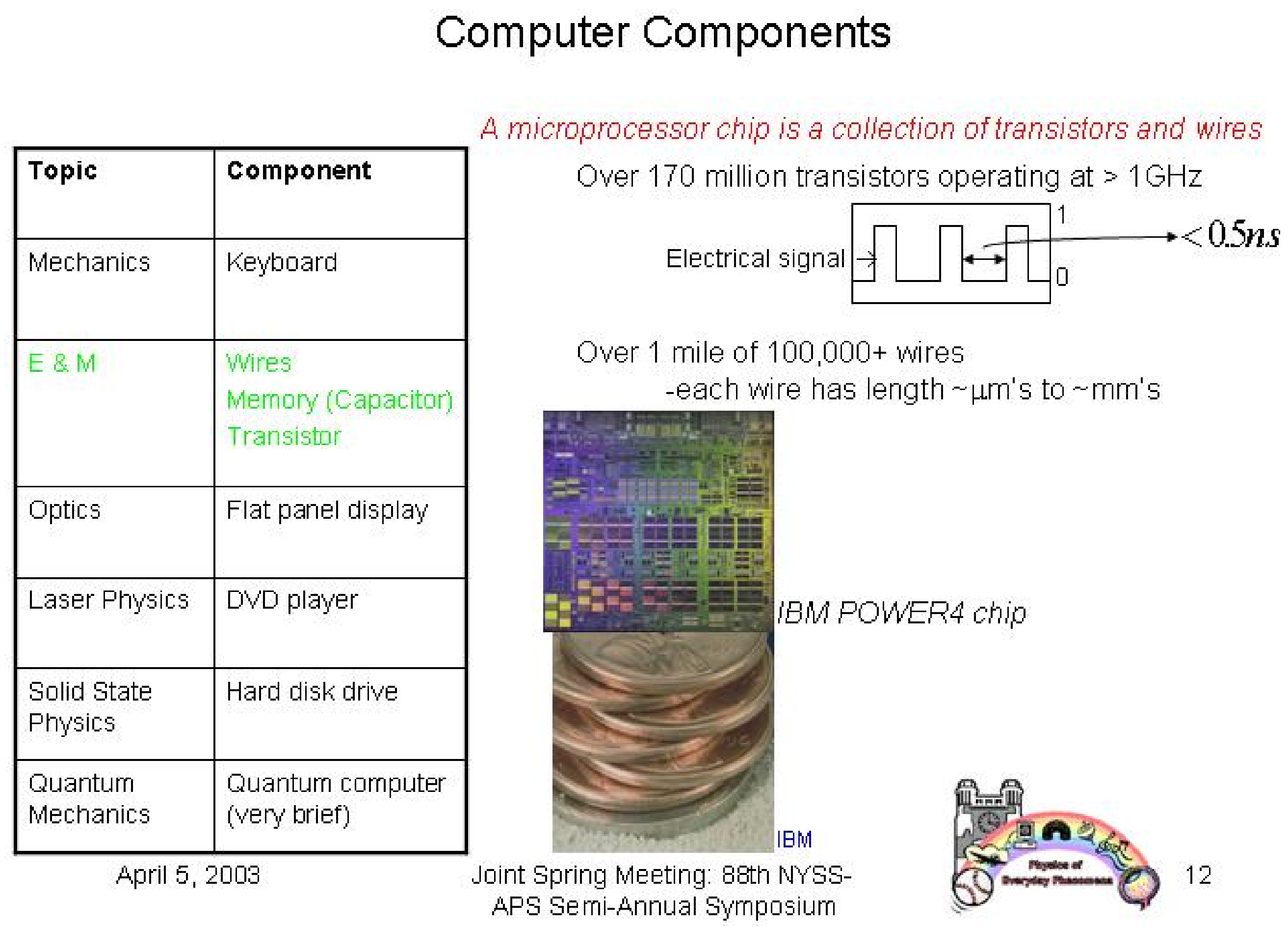
Packaged POWER4

April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

11

Fig. 11. Images of POWER4 chip (center), wafers (upper left), packaged POWER4 chip (lower left), top view of copper wiring (upper right), and cross-sectional view of copper wiring (lower right).



Computer Components

A microprocessor chip is a collection of transistors and wires

Topic	**Component**
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

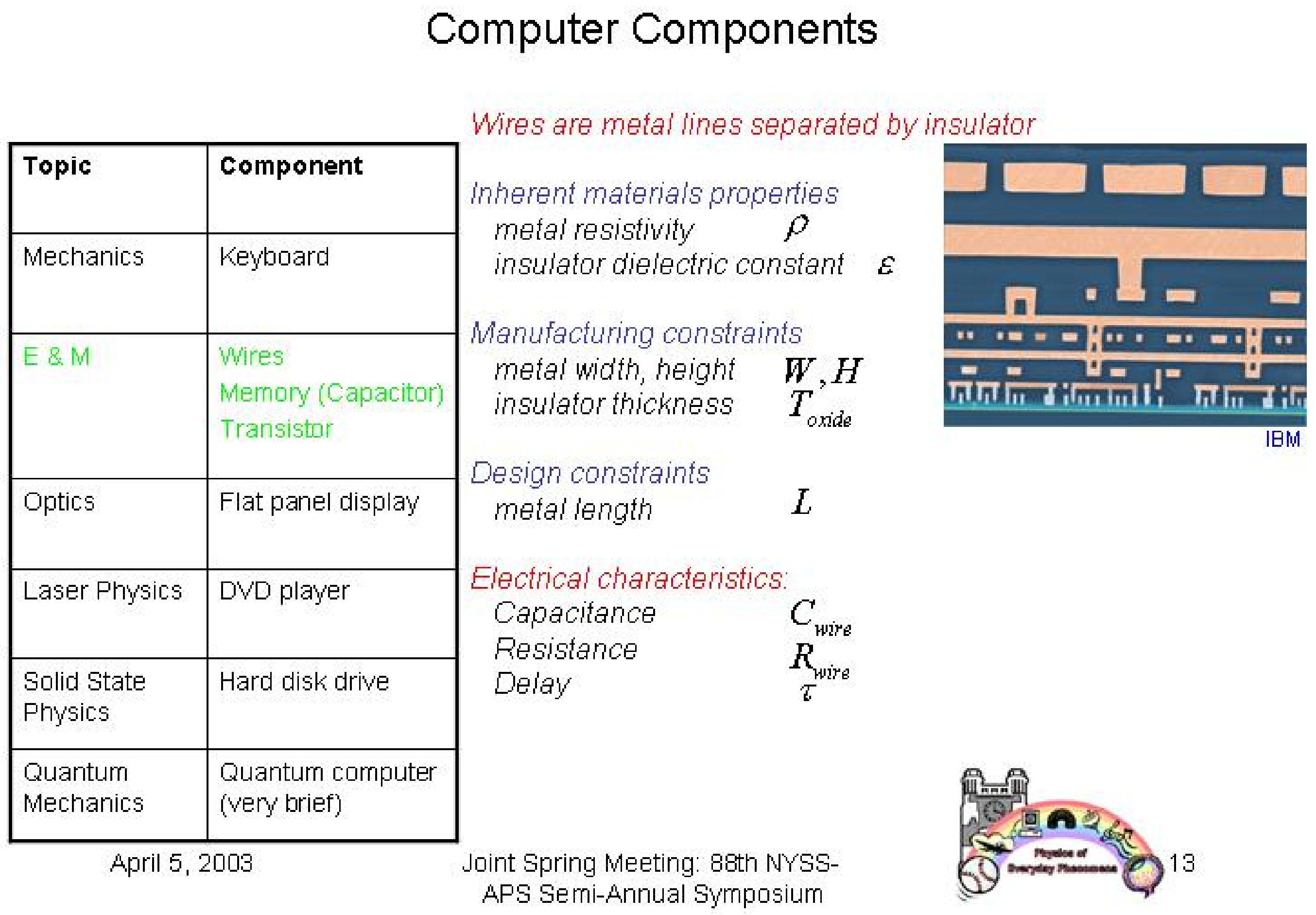
Over 170 million transistors operating at > 1GHz

Over 1 mile of 100,000+ wires
-each wire has length ~µm's to ~mm's

IBM POWER4 chip

April 5, 2003 Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium 12

Fig. 12. A microprocessor is a collection of wires and transistors, shown with an image of a POWER4 chip on a stack of copper pennies.



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Wires are metal lines separated by insulator

Inherent materials properties
metal resistivity ρ
insulator dielectric constant ε

Manufacturing constraints
metal width, height W, H
insulator thickness T_{oxide}

Design constraints
metal length L

Electrical characteristics:
Capacitance C_{wire}
Resistance R_{wire}
Delay τ

April 5, 2003
Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium
13

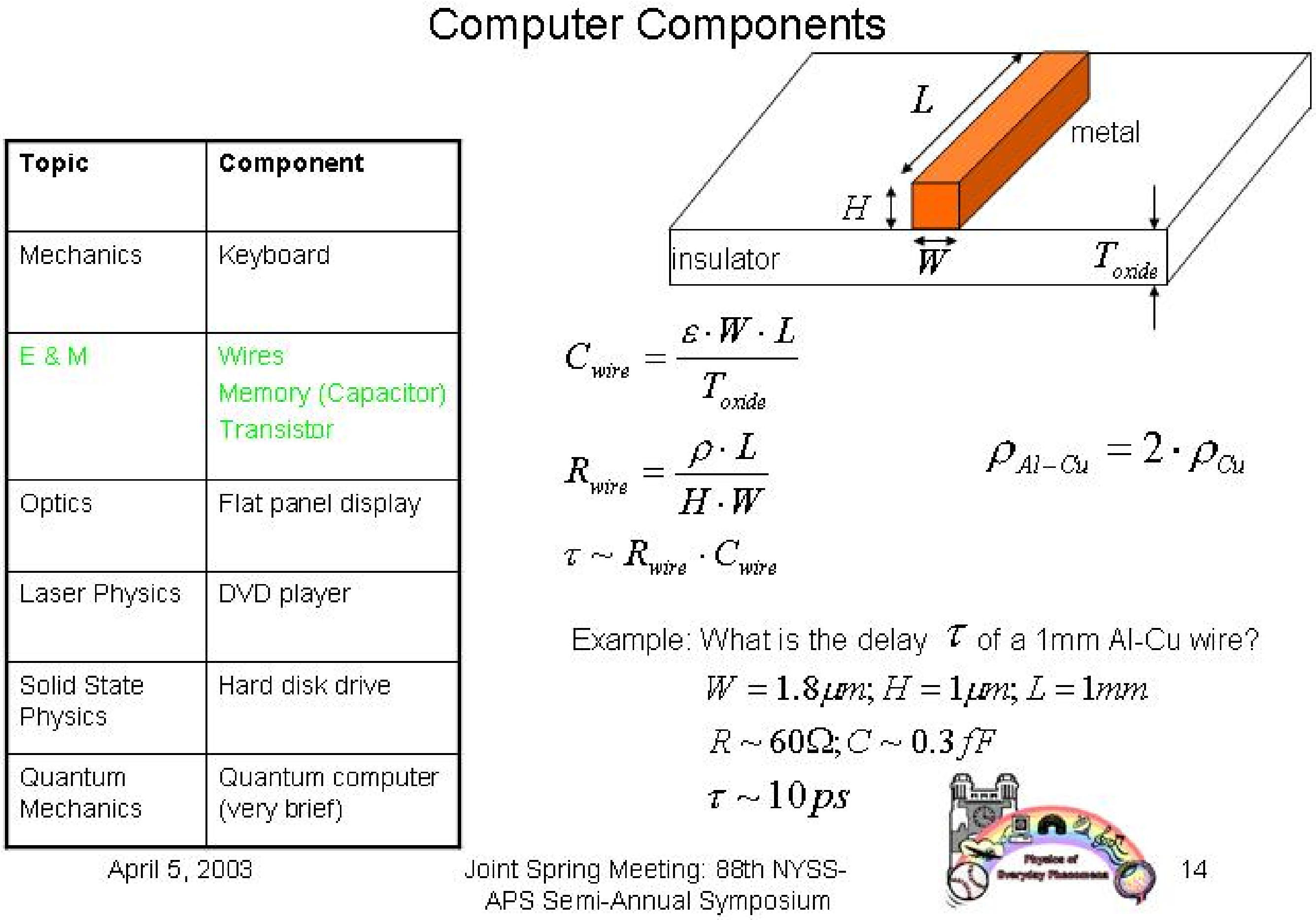
Fig. 13. Electricity and Magnetism: Wires are metal lines separated by dielectric.

VI. Electricity and Magnetism: Wires, Memory (Capacitor), and Transistor

The three types of computer components that I will discuss now to illustrate electricity and magnetism are wires, memory (a capacitor), and a transistor.

A. Wires

Wires are metal lines characterized by resistivity ρ and separated by insulator with dielectric constant ϵ. Manufacturing constraints set the metal width and height and insulator thickness, and design constraints set the wire length. In some cases, we find that the wires are unnecessarily long, so it is important also to design the wires efficiently. Electrical characteristics that result from the choice of material for the wires and their design constraints are their capacitance, resistance, and delay, where the term delay refers to the time required to propagate a signal from one end of the wire to the other (see Figure 13).



Computer Components

Topic	**Component**
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

$$C_{wire} = \frac{\varepsilon \cdot W \cdot L}{T_{oxide}}$$

$$R_{wire} = \frac{\rho \cdot L}{H \cdot W}$$

$$\rho_{Al-Cu} = 2 \cdot \rho_{Cu}$$

$$\tau \sim R_{wire} \cdot C_{wire}$$

Example: What is the delay τ of a 1mm Al-Cu wire?

$$W = 1.8\mu m;\ H = 1\mu m;\ L = 1mm$$

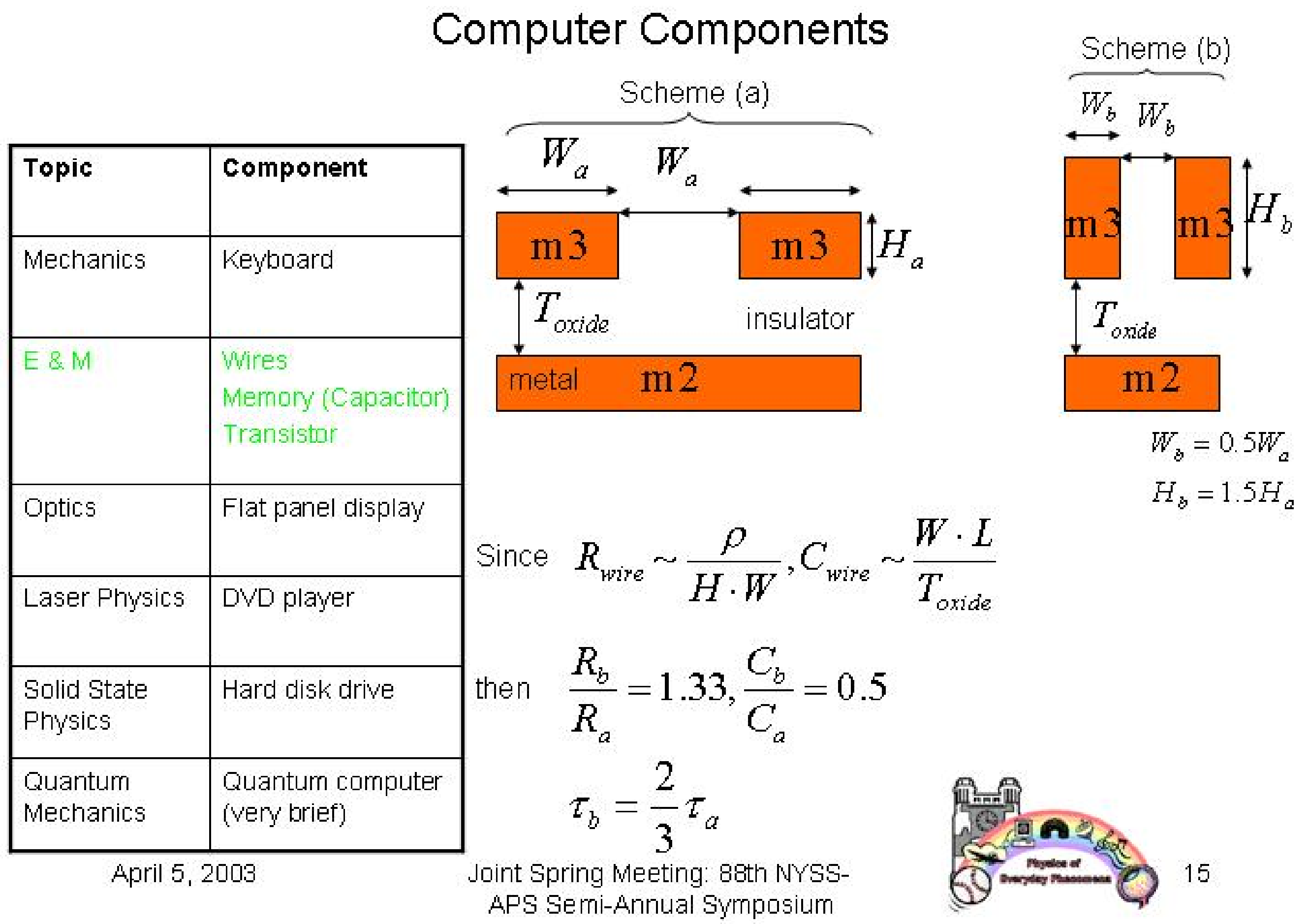
$$R \sim 60\Omega;\ C \sim 0.3fF$$

$$\tau \sim 10ps$$

April 5, 2003 Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium 14

Fig. 14. Electricity and Magnetism: A closer look at an isolated metal wire.

Let's look more closely at one typical isolated metal wire, shown here with its length greater than its width and height. The wire capacitance is given by the dielectric constant times the width W and the length L divided by the oxide thickness, and the resistance is given by the resistivity times the length L divided by the height H times the width W, and the wire delay is proportional to the product resistance times capacitance. If the goal is to increase microprocessor speed, we need to decrease wire delay. What are some things we can do? Well, these expressions tell us that if we can find a material with lower insulator dielectric constant, and metal with lower resistivity (such as for copper instead of aluminum-copper), or find a manufacturing process in which we can make the wires taller (height H increases), then we can reduce wire delay. What about from a design perspective? Since the delay is proportional to the square of the length, if the wires are even slightly sloppily wired with excess length, then the wire delay is increased (see Figure 14).



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

$W_b = 0.5W_a$

$H_b = 1.5H_a$

Since $R_{wire} \sim \dfrac{\rho}{H \cdot W}, C_{wire} \sim \dfrac{W \cdot L}{T_{oxide}}$

then $\dfrac{R_b}{R_a} = 1.33, \dfrac{C_b}{C_a} = 0.5$

$$\tau_b = \frac{2}{3}\tau_a$$

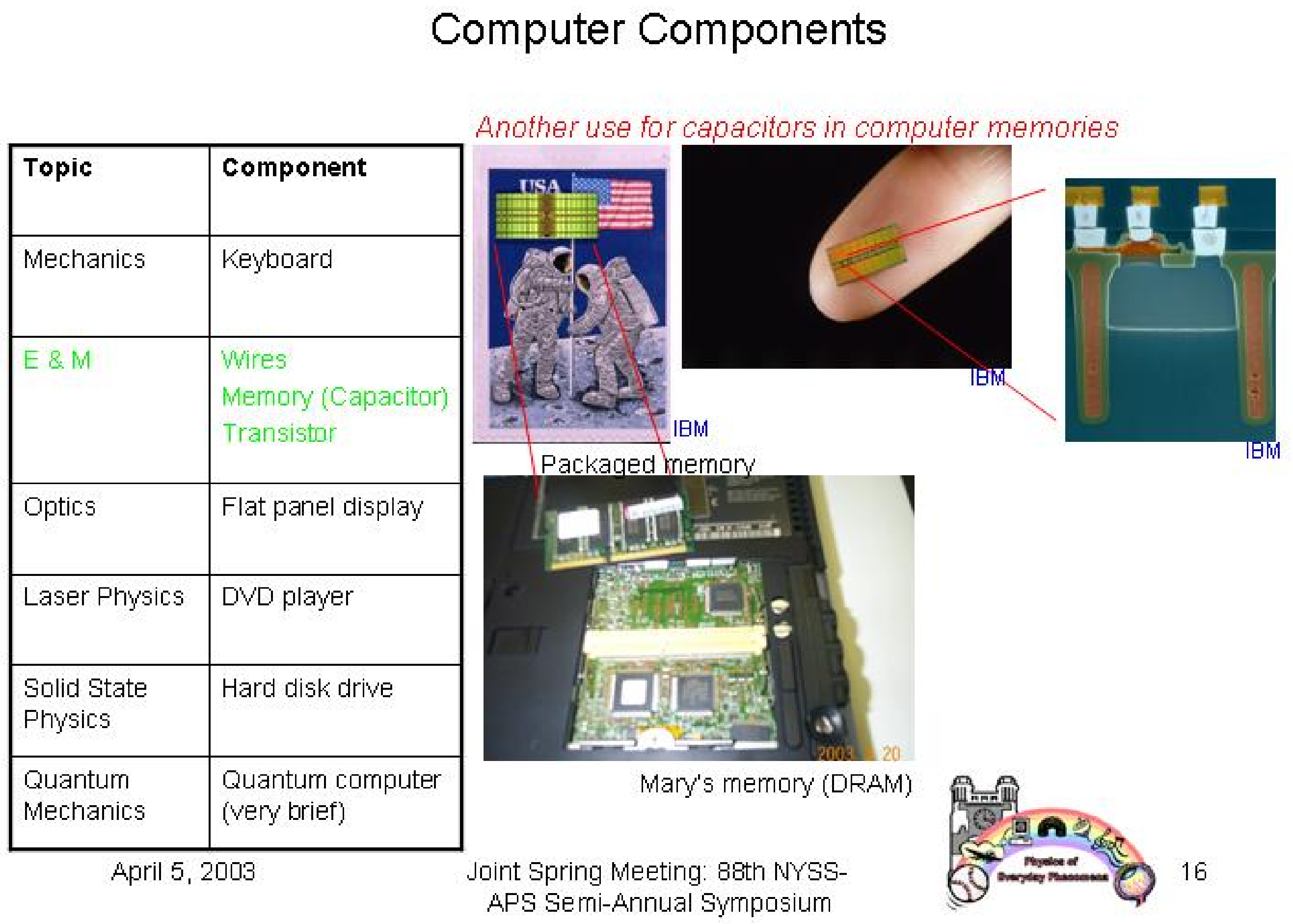
April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

15

Fig. 15. Electricity and Magnetism: Two wiring schemes, shown with two different cross-sections as scheme (a) and scheme (b).

A closer look at two different manufacturing designs for wires, as shown in Figure 15, will also give us more insight. The wiring cross-section shown in Scheme (a) shows wide, short wires, and wiring Scheme (b) shows tall, skinny wires. Although the wire resistance of Scheme (b) is greater than that of Scheme (a), the capacitance of (b) is much less, so that the delay of a taller, thinner wire is less than that of a wide, short wire, where both wires have equal length. In fact the wires in our designs are more similar to (b).



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Another use for capacitors in computer memories

Mary's memory (DRAM)

April 5, 2003

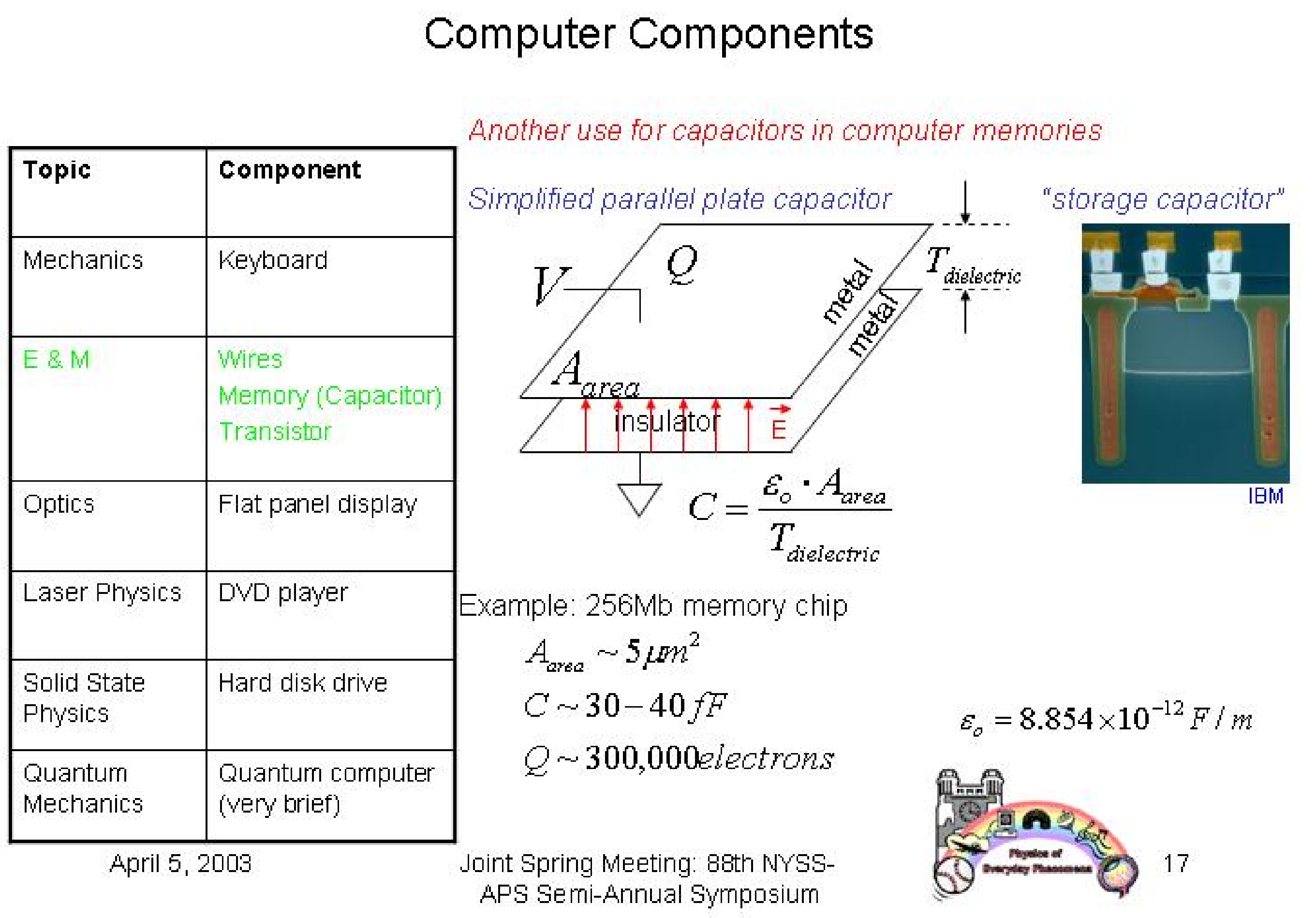
Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

16

Fig. 16. Electricity and Magnetism: A capacitor in a computer memory.

B. *Memory (a capacitor)*

Another use for capacitors is in computer memories. The images shown in Figure 16 show $256MB$ memory chips. The image below is a packaged memory chip taken from the underside of my computer, and if we zoom in on the one on the right-hand-side and take a cross-section, we see the detail of a so-called "deep trench storage capacitor" used in the memory chip.



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Another use for capacitors in computer memories

Simplified parallel plate capacitor

"storage capacitor"

$$C = \frac{\varepsilon_o \cdot A_{area}}{T_{dielectric}}$$

Example: 256Mb memory chip

$A_{area} \sim 5\mu m^2$

$C \sim 30-40 fF$

$Q \sim 300{,}000 electrons$

$\varepsilon_o = 8.854 \times 10^{-12} F/m$

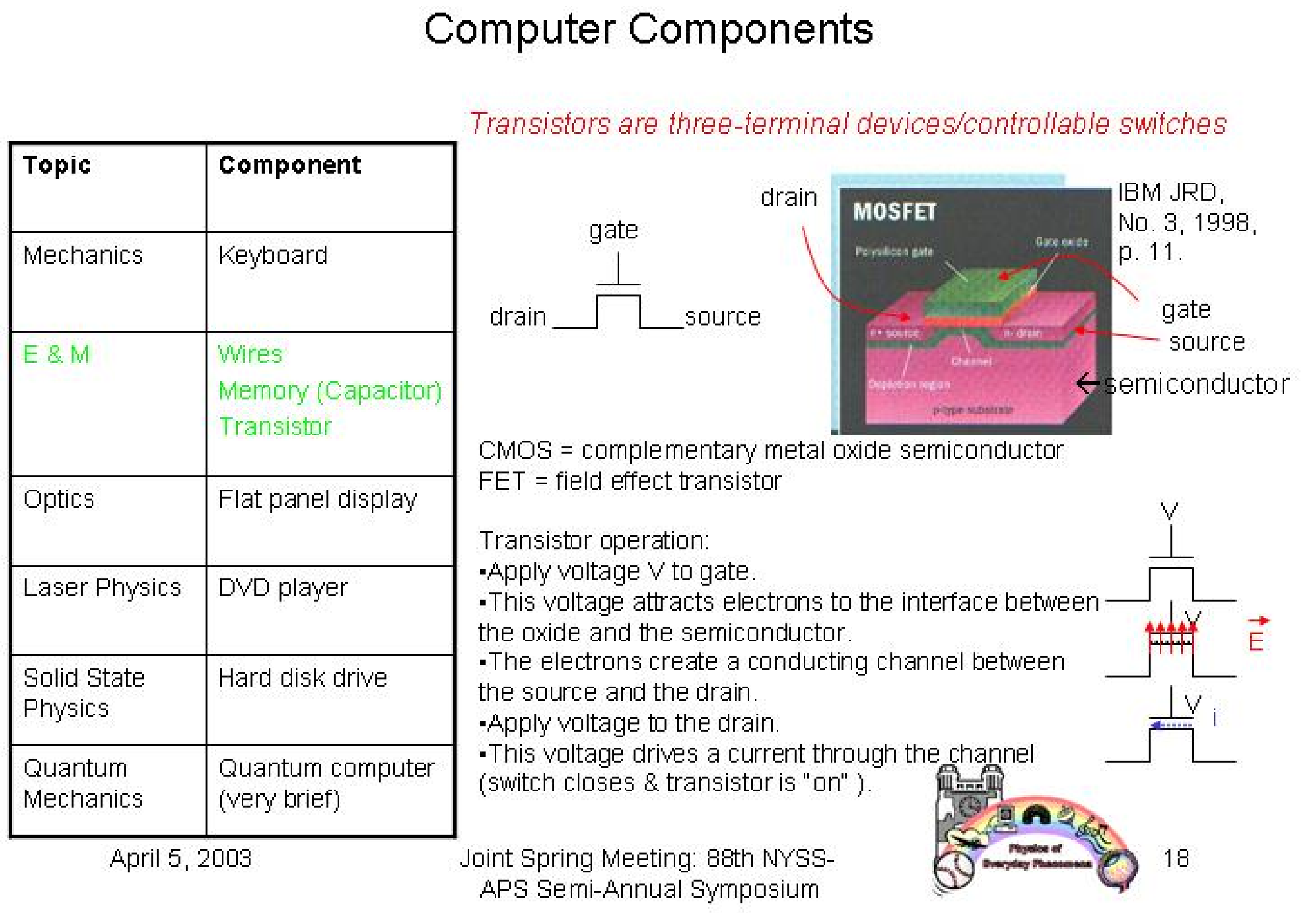
April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

17

Fig. 17. Electricity and Magnetism: A capacitor, shown in the diagram on the left and in cross-section on the right.

Let's look more closely at a parallel plate capacitor, shown in Figure 17 in the left-hand diagram. A voltage V is applied to the metal top plate with area A_{area}, and the bottom plate is grounded. This capacitor can store a certain number of electrons. The capacitor can hold more charge $Q = C \times V$ if the dielectric thickness is reduced, materials with higher dielectric constant are used, or the area is increased. To get the cross-section shown in this figure, we take the capacitor and stretch it into a deep trench, which allows us to pack many more capacitors per silicon area than if they were spread out as shown on the left side of the figure. For example, the capacitance Q is chosen such that a typical capacitor can hold $300,000$ electrons.



Computer Components

Transistors are three-terminal devices/controllable switches

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

IBM JRD, No. 3, 1998, p. 11.

CMOS = complementary metal oxide semiconductor
FET = field effect transistor

Transistor operation:
- Apply voltage V to gate.
- This voltage attracts electrons to the interface between the oxide and the semiconductor.
- The electrons create a conducting channel between the source and the drain.
- Apply voltage to the drain.
- This voltage drives a current through the channel (switch closes & transistor is "on").

April 5, 2003 Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

Physics of Everyday Phenomena

Fig. 18. Electricity and Magnetism: The transistor.

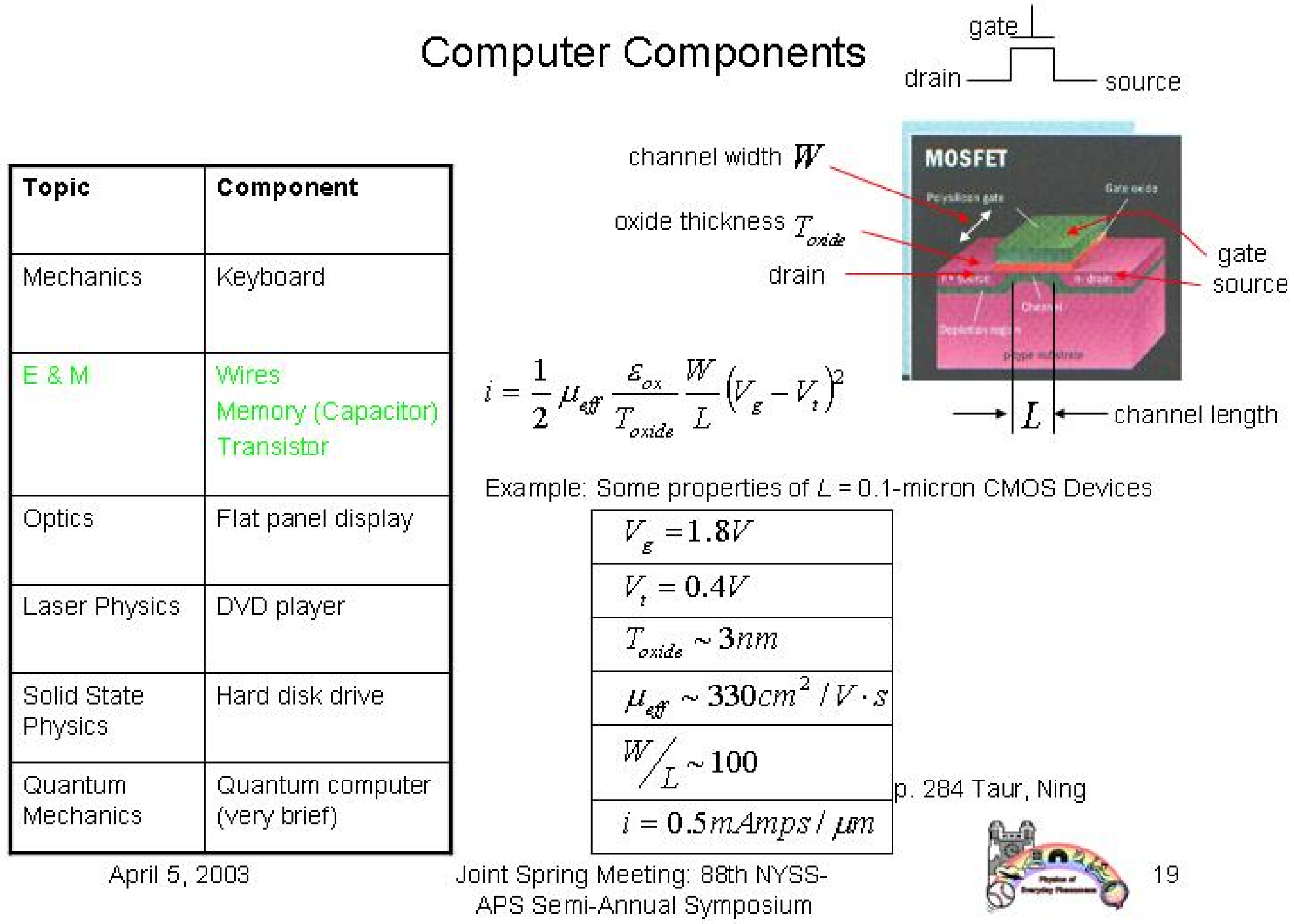
C. Transistors

The building block of the central processing unit (CPU), cache, and main memory is the transistor, a three-terminal device also called a controllable switch. In the version typically used in the semiconductor industry to make integrated circuits, the three terminals are made with metal and are known by the names *gate*, *drain*, and *source*, and the physics of these devices is becoming more and more complicated as the devices shrink from 0.5-microns, that is, the channel length between the drain and the source, to 0.1-micron devices and smaller. A cross-section of a transistor is shown on the right of Figure 18.

A very simplified view of the operation of a transistor is given by the following series of steps:

- First, a voltage V is applied to the gate. This voltage sets up an electric field in this region called the channel because typically the semiconductor is grounded (ground not shown).
- This voltage attracts electrons to the interface between the oxide under the gate and the semiconductor (silicon). The electrons create a conducting channel between the source and the drain.
- When a voltage V is applied to the drain, a current flows through the channel and the transistor is *ON*.

One challenge is that as modern transistors shrink, they are no longer operating as true switches, but as *dimmers*. That is, in physics terms, there is a great deal of leakage and current flows even when the transistors are supposed to be *OFF*.



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

$$i = \frac{1}{2}\mu_{eff}\frac{\varepsilon_{ox}}{T_{oxide}}\frac{W}{L}\left(V_g - V_t\right)^2$$

Example: Some properties of L = 0.1-micron CMOS Devices

$V_g = 1.8V$
$V_t = 0.4V$
$T_{oxide} \sim 3nm$
$\mu_{eff} \sim 330 cm^2 / V \cdot s$
$W/L \sim 100$
$i = 0.5 mAmps / \mu m$

p. 284 Taur, Ning

April 5, 2003

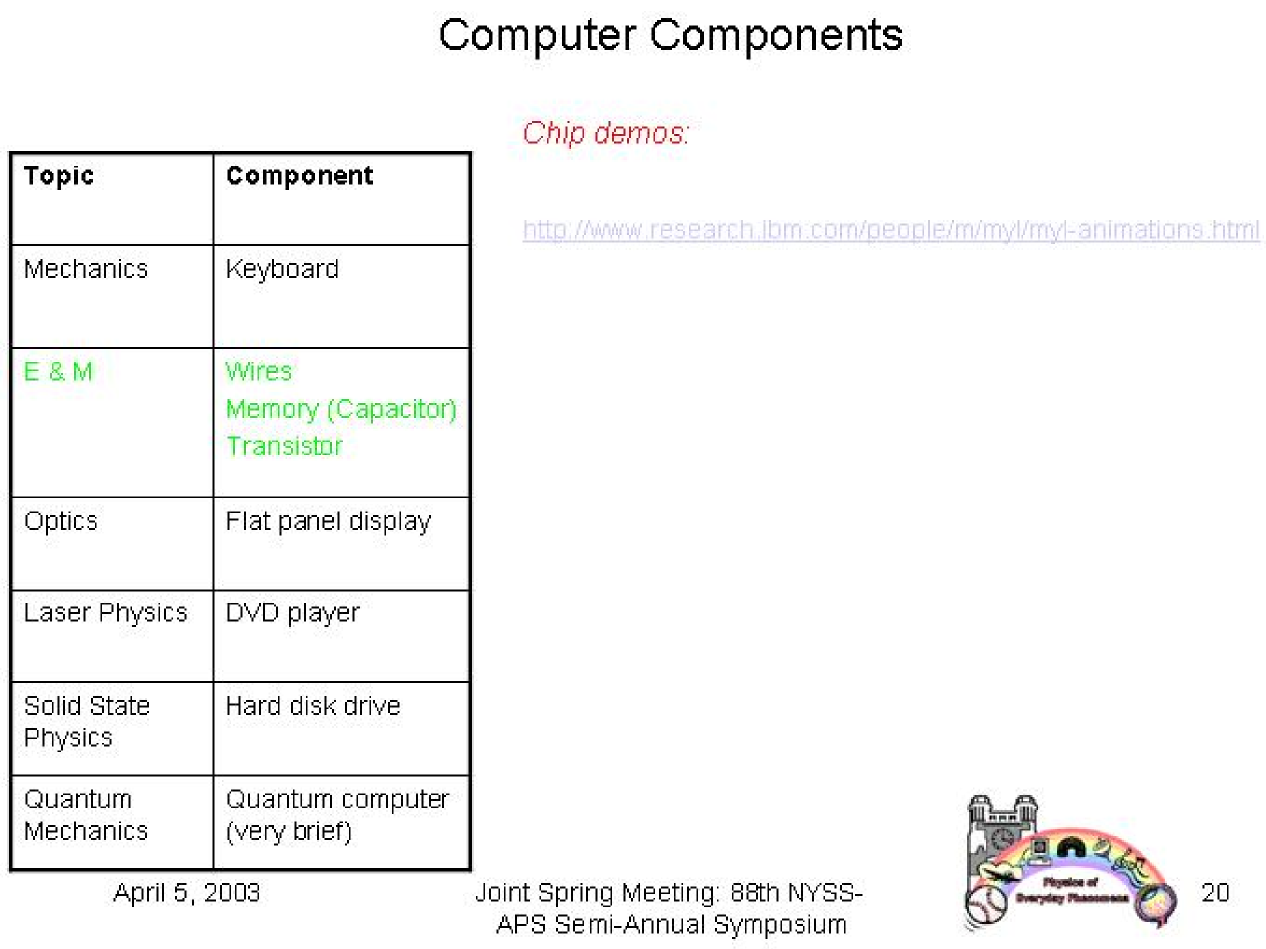
Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

19

Fig. 19. Electricity and Magnetism: The transistor (continued).

Figure 19 shows a few characteristics of a transistor with 0.1-micron channel length. For a gate voltage of 1.8Volts, the current in the channel is on the order of 0.5mAmps per micron.

The reason that transistor keep shrinking is that they operate faster when the channel length is reduced. The need for faster transistors and wires has been driving device development, the physics of these devices, the techniques used to make them, materials physics, and optical lithography for the past several decades. I will come back to this point at the end of the talk and discuss some examples where physicists who specialize in different areas are working in different departments at IBM.



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Chip demos:

http://www.research.ibm.com/people/m/myl/myl-animations.html

April 5, 2003

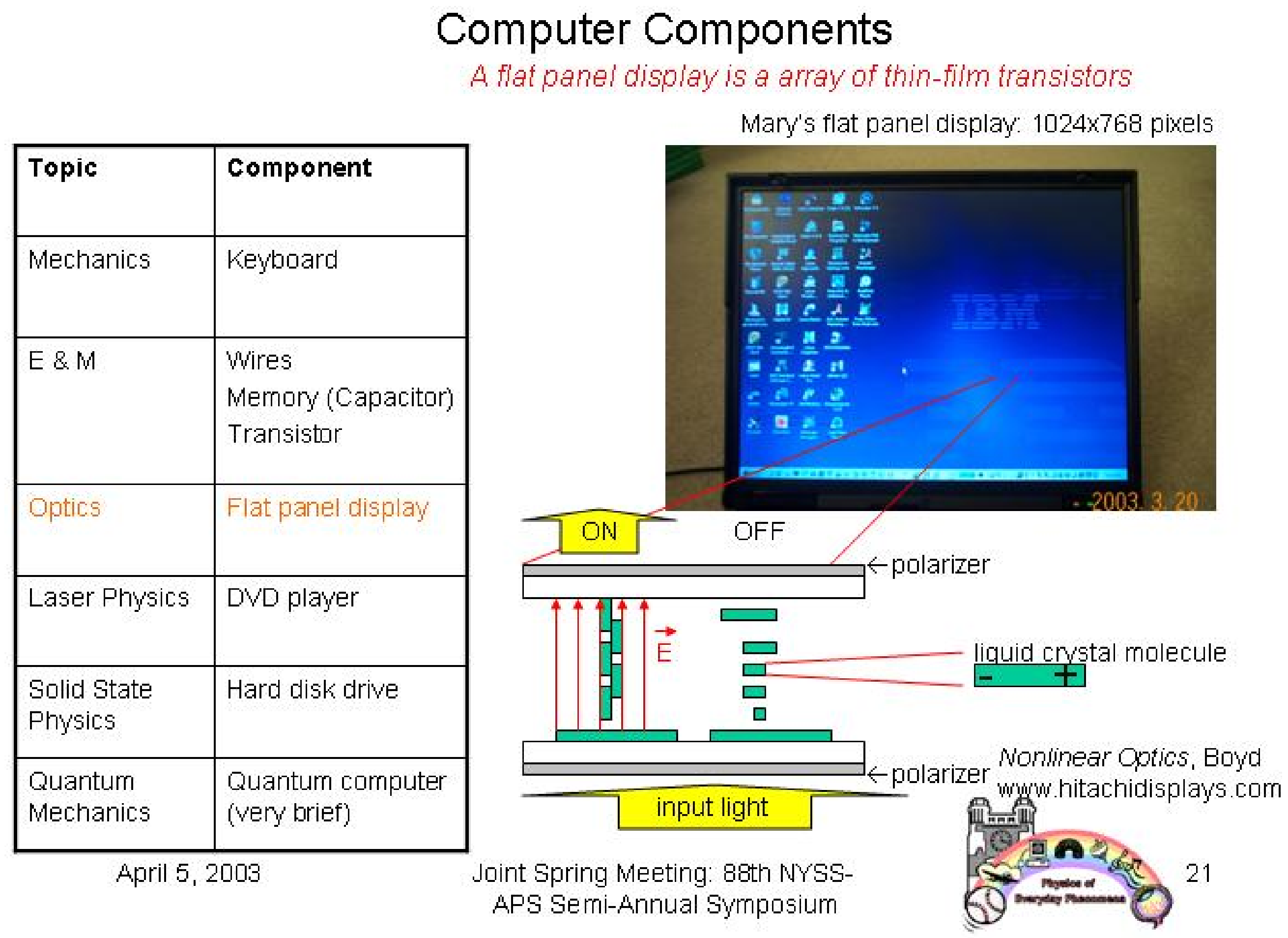
Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

20

Fig. 20. My animations of the POWER4 chip and POWER4 Instruction Fetch Unit are available on the internet at http://www.research.ibm.com/people/m/myl/myl-animations.html.

VII. DEMONSTRATIONS

Several animations that I have made of the POWER4 chip are available on the internet at the URL shown in Figure 20: http://www.research.ibm.com/people/m/myl/myl-animations.html. The animation called “POWER4 Chip: Flight of a PowerPC STORE instruction” shows the path followed by a STORE instruction in the chip. In this path, a STORE instruction is fetched from a subarray in the L2 cache by the Instruction Fetch Unit (IFU). It gets decoded in the Instruction Decode Unit (IDU) and is dispatched to the Instruction Sequencing Unit (ISU). Later, it is issued from the ISU to the Load Store Unit (LSU). The LSU picks up the data to be stored from a register file (here, in the Fixed Point Unit [FXU]) and stores it in an L2 subarray.



Computer Components

A flat panel display is a array of thin-film transistors

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Mary's flat panel display: 1024x768 pixels

Nonlinear Optics, Boyd
www.hitachidisplays.com

April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

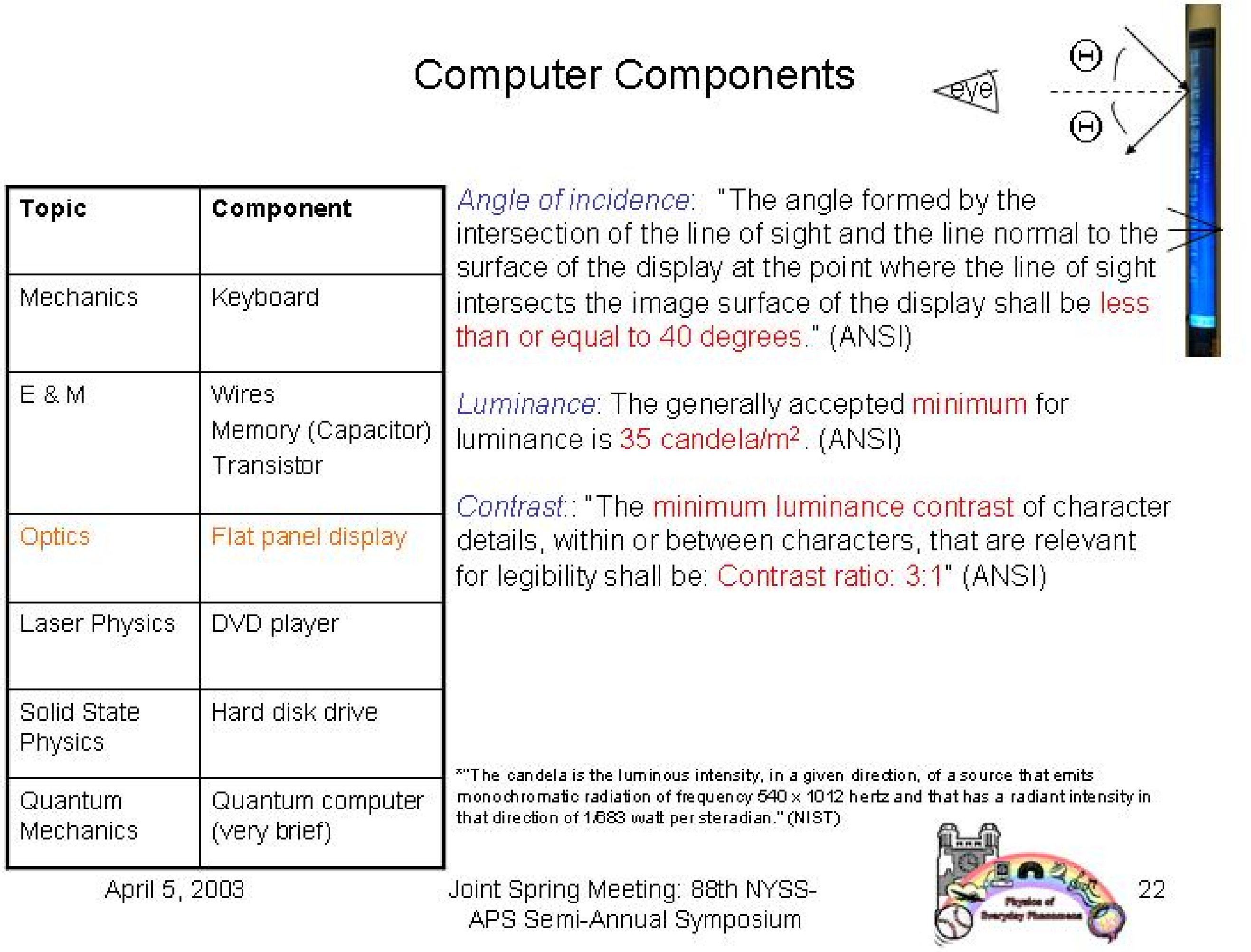
21

Fig. 21. Optics: Flat panel display.

VIII. OPTICS: FLAT PANEL DISPLAY

In the remainder of this talk I will discuss three components that illustrate basic knowledge of optics, lasers, and solid-state physics. Our approach is a simple, multidisciplinary approach to provide motivation to physics students early in their careers about how the physics they learn in each of these topics and classes is useful.

Let's first consider the flat panel display shown in Figure 21. Light and portable, it permits us to carry laptops with screens rather than cathode-ray-tube monitors. The size of my screen consists of an array of 1024 pixels wide $\times$ 768 pixels tall. It's just an array of thin film transistors, where each transistor is composed of twisted liquid crystals that align parallel to an applied electric field to rotate the polarization of the light, permitting light applied at the back of the screen to pass through to the eyes.



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Angle of incidence: "The angle formed by the intersection of the line of sight and the line normal to the surface of the display at the point where the line of sight intersects the image surface of the display shall be less than or equal to 40 degrees." (ANSI)

Luminance: The generally accepted minimum for luminance is 35 candela/m^2. (ANSI)

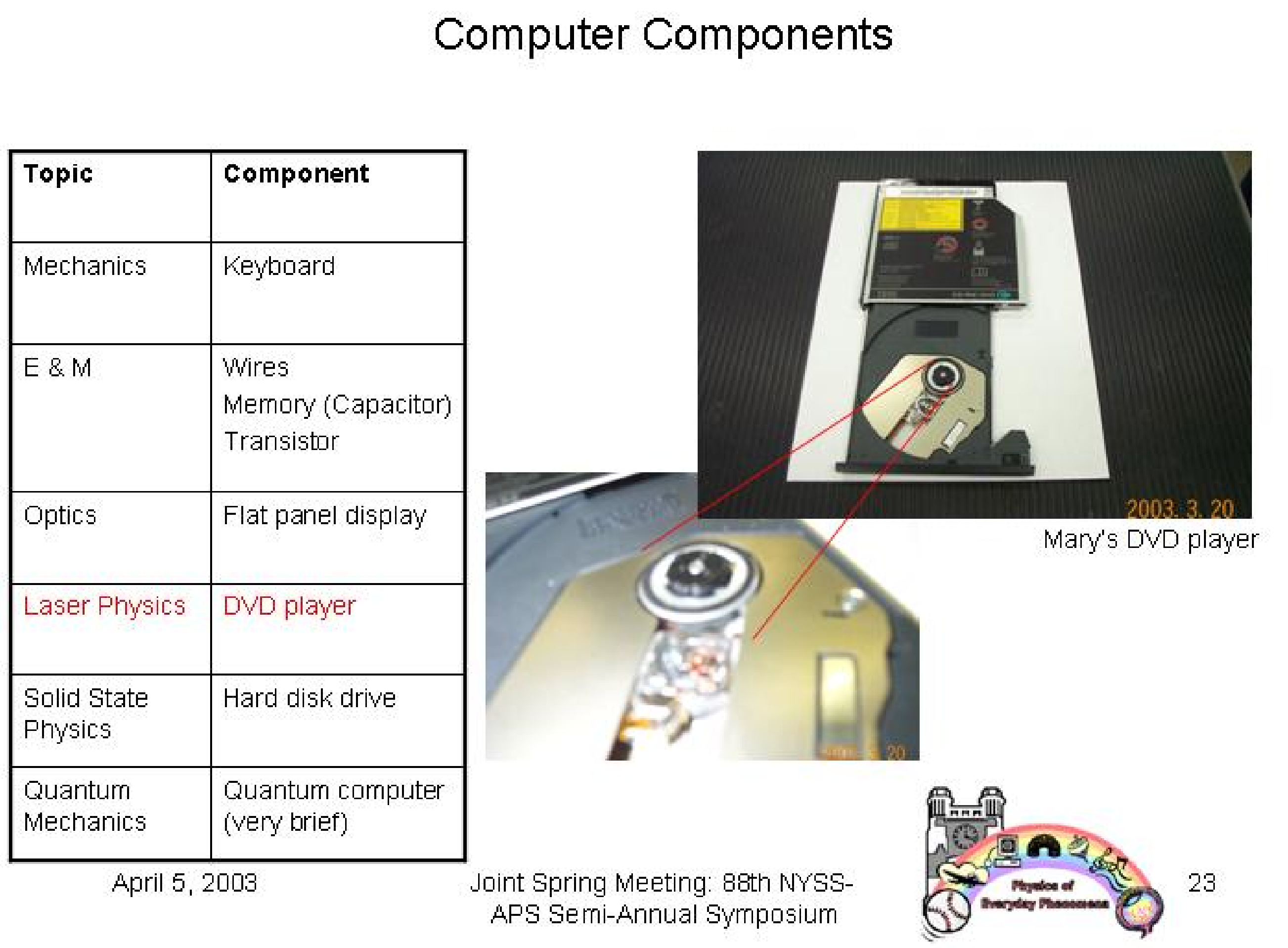
Contrast:: "The minimum luminance contrast of character details, within or between characters, that are relevant for legibility shall be: Contrast ratio: 3:1" (ANSI)

*"The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 1012 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian." (NIST)

April 5, 2003 Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium 22

Fig. 22. Optics: Flat panel display (continued).

Light emitted by this pixel is shown in Figure 22 as a side view of the flat panel display. Also present is ambient light, such as light from overhead lamps, which obeys Snell’s Law in reflecting from the screen. To keep the reflected light from overwhelming the eyes, the American National Standards Institute recommends that the user keeps the angle between the line of sight and the surface normal below 40 degrees.



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Mary's DVD player

April 5, 2003

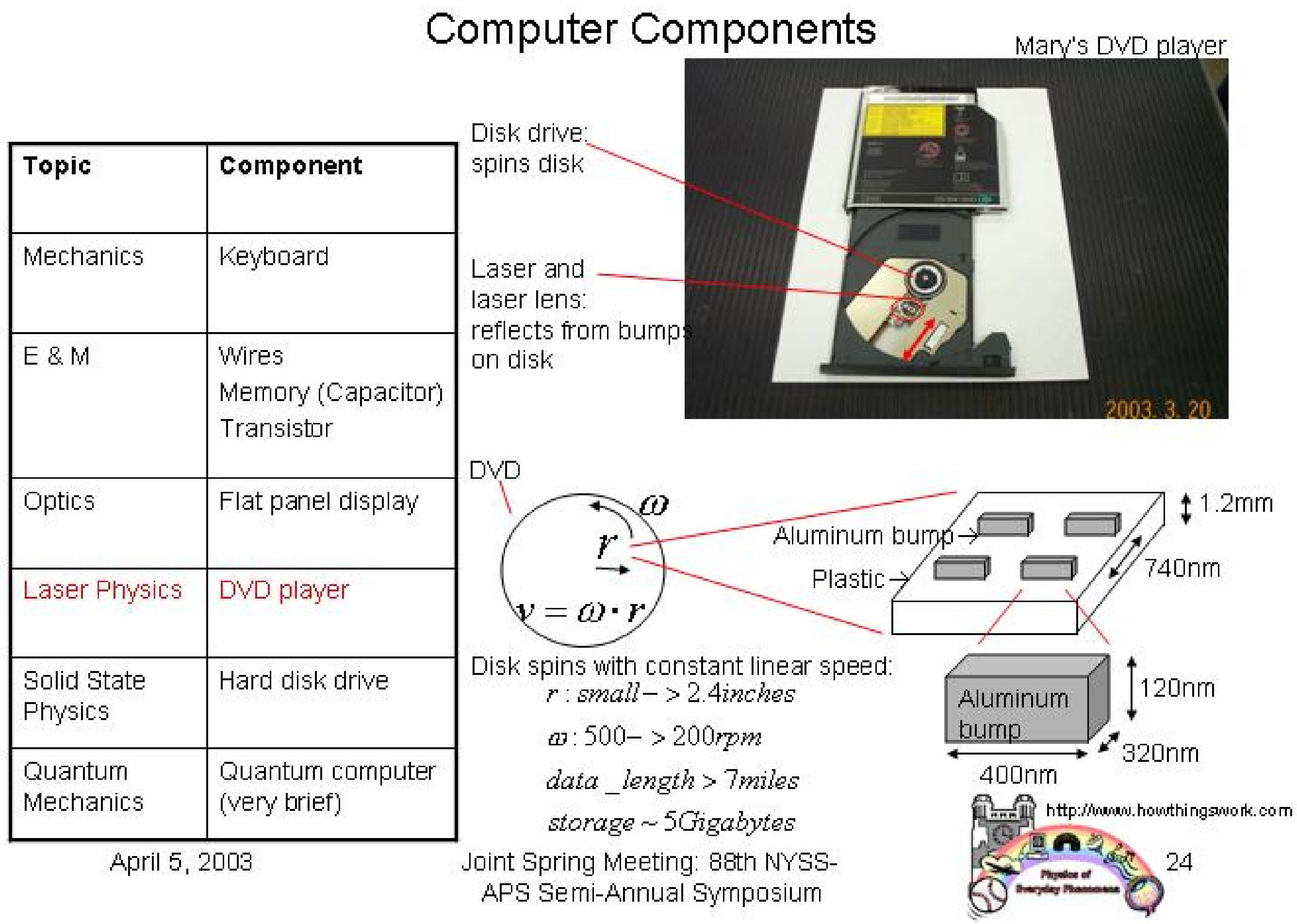
Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

23

Fig. 23. Laser physics: DVD player.

IX. LASER PHYSICS: DVD PLAYER

We now discuss laser physics and a bit of mechanics in the DVD player, or Digital Video Disk player. Figure 23 shows the DVD player after it has been removed from my computer with the important bits shown slightly larger in the image below.



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Mary's DVD player

Disk drive: spins disk

Laser and laser lens: reflects from bumps on disk

2003. 3. 20

Disk spins with constant linear speed:

$r : small -> 2.4 inches$

$\omega : 500 -> 200 rpm$

$data\_length > 7 miles$

$storage \sim 5 Gigabytes$

http://www.howthingswork.com

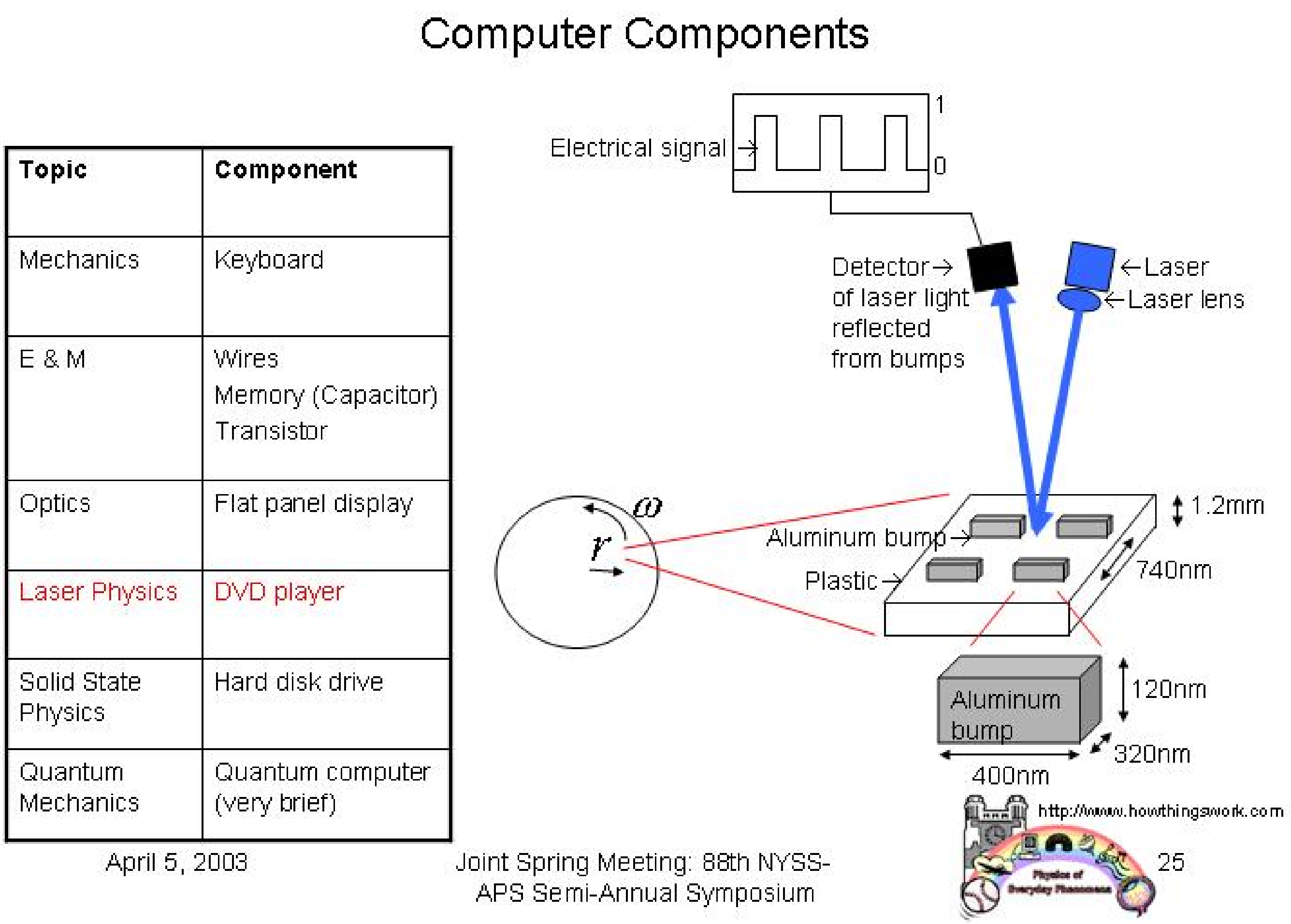
April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

24

Fig. 24. Laser physics: DVD player (continued).

As shown in Figure 24, the DVD player has a disk drive which spins a flat disk at constant linear speed. The disk contains information displayed as aluminum bumps along tracks that spiral outward from the center of the disk, starting with the beginning of a DVD or CD. The disk drive rotates with high angular velocity ω on the order of 500 revolutions per minute and as the information in the tracks is read, gradually slows to 200 revolutions per minute as it approaches the perimeter, approximately 7 miles and 5 Gigabytes later, depending on the details of the construction of the DVD.



Computer Components

Topic	**Component**
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

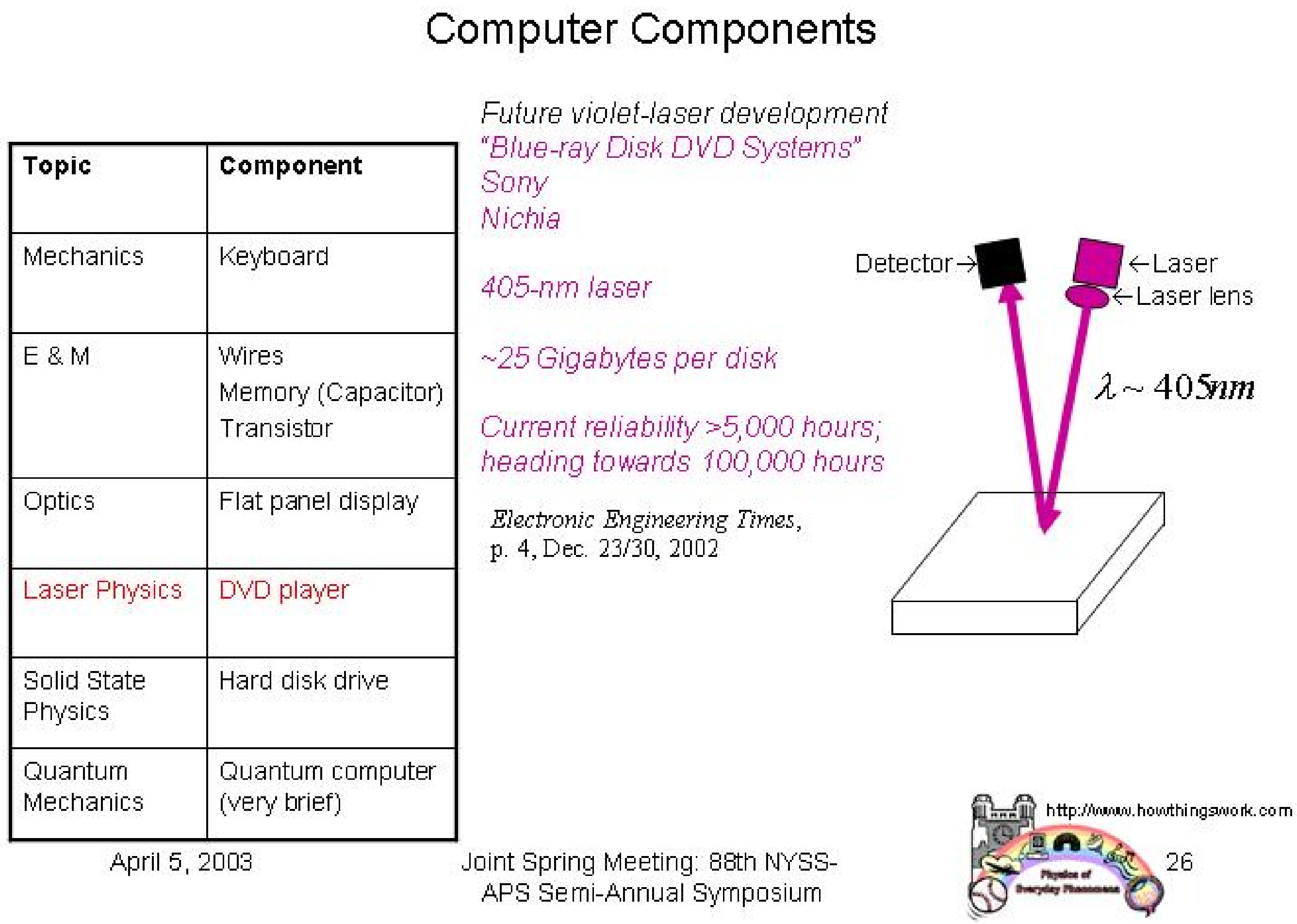
April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

25

Fig. 25. Laser physics: DVD player (continued, with details of laser and detection schematic).

The laser described in Figure 24 can be illustrated as shown in Figure 25. The laser is focused by a laser lens on each of the tracks, where it is reflected from the DVD into a photodetector that converts the light into an electrical signal, registering a nonzero signal when light is reflected from the DVD and registering a zero when the laser light is deflected from the detector as it passes over an aluminum bump.



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Future violet-laser development
"Blue-ray Disk DVD Systems"
Sony
Nichia

405-nm laser

~25 Gigabytes per disk

Current reliability >5,000 hours; heading towards 100,000 hours

Electronic Engineering Times, p. 4, Dec. 23/30, 2002

April 5, 2003

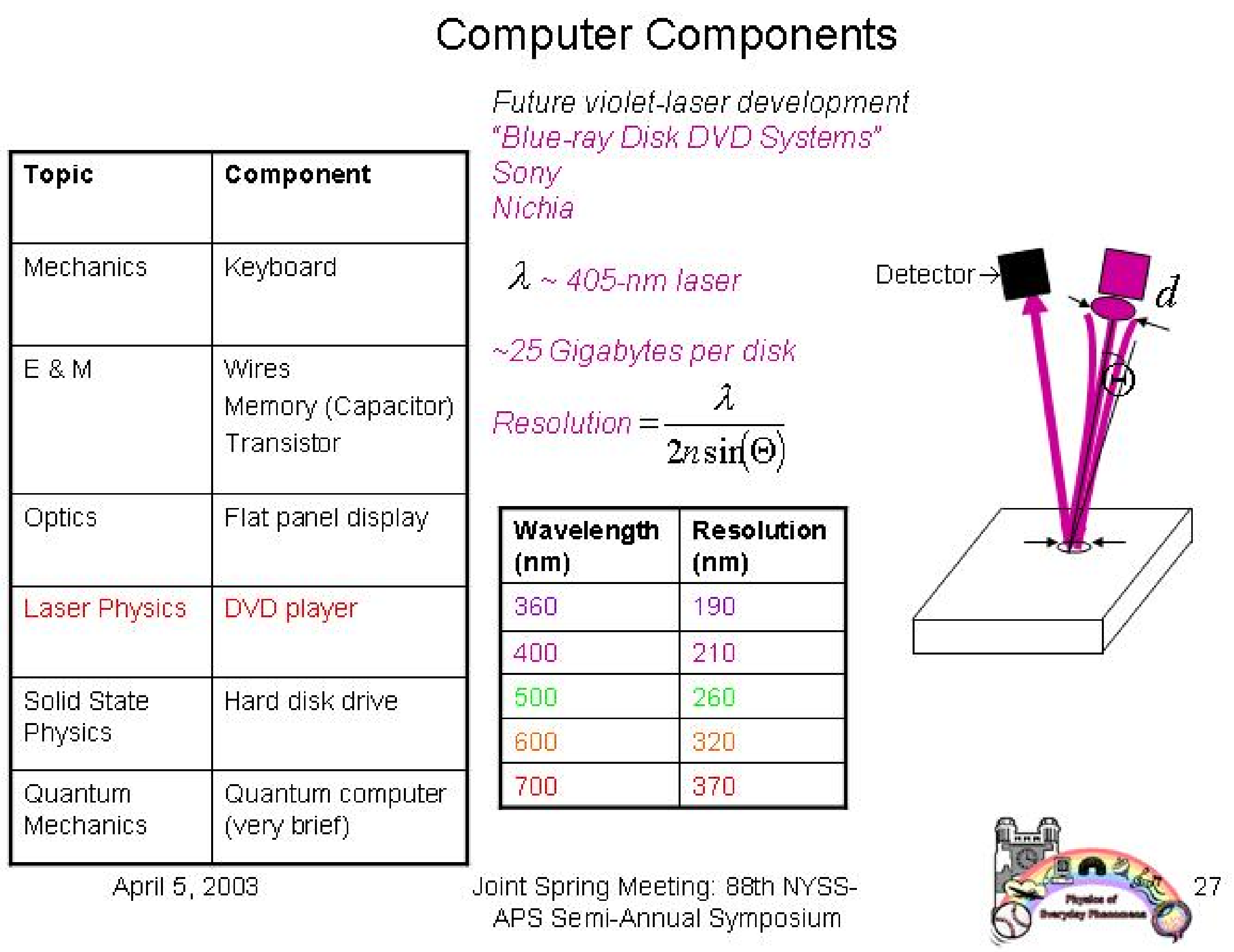
Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

26

http://www.howthingswork.com

Fig. 26. Laser physics: DVD player (Blue-ray Disk DVD Systems).

Development of violet lasers with smaller wavelength of $405nm$ as shown in Figure 26 will allow detection of ever smaller bumps and permit storage of 25 Gigabits per 4.8-inch disk.



Computer Components

Topic	**Component**
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Future violet-laser development
"Blue-ray Disk DVD Systems"
Sony
Nichia

λ ~ 405-nm laser

~25 Gigabytes per disk

$$\text{Resolution} = \frac{\lambda}{2n\sin(\Theta)}$$

Wavelength (nm)	**Resolution (nm)**
360	190
400	210
500	260
600	320
700	370

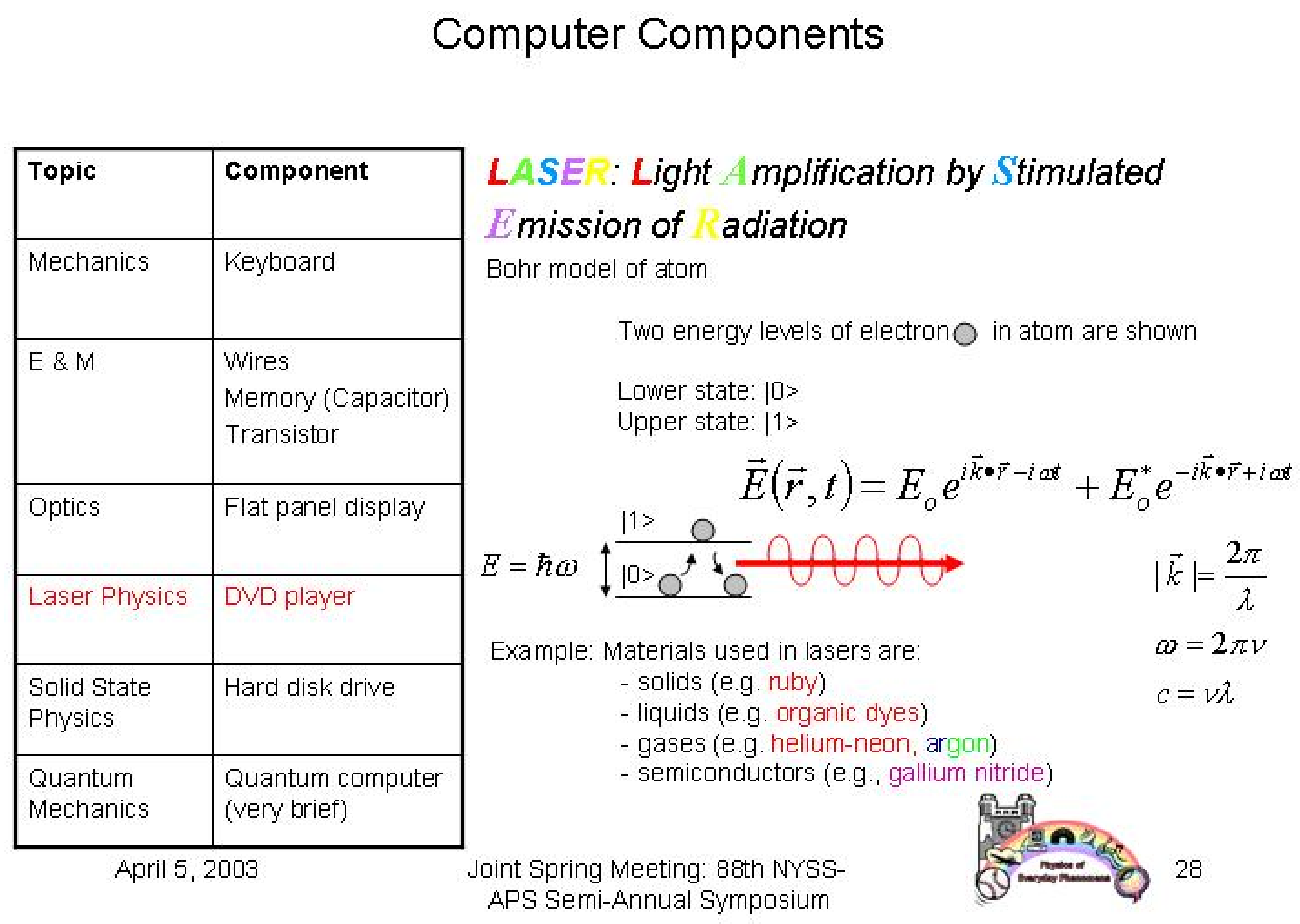
April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

27

Fig. 27. Laser physics: DVD player (resolution).

One reason we care about developing lasers with even smaller wavelength is that these lasers can have improved resolution, or a smaller resolvable distance between two objects, where resolution is given by the wavelength divided by $2 \times n \times sin\theta$, where n is the refractive index of the imaging medium and θ is one-half of the angular aperture of the lens. For air, the refractive index is unity, and the maximum value for θ is 90 degrees. Therefore, the sine of the angle θ has a maximum value of 1.0, so the theoretical minimum resolution when operating when air as the imaging medium is half the wavelength, or $\lambda/2$. The resolution for light with different wavelengths is shown in Figure 27.



Computer Components

Topic	**Component**
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

LASER: Light Amplification by Stimulated Emission of Radiation

Bohr model of atom

Two energy levels of electron ● in atom are shown

Lower state: |0>
Upper state: |1>

$$\vec{E}(\vec{r},t) = E_o e^{i\vec{k}\bullet\vec{r} - i\omega t} + E_o^* e^{-i\vec{k}\bullet\vec{r} + i\omega t}$$

$$E = \hbar\omega$$

$$|\vec{k}| = \frac{2\pi}{\lambda}$$

$$\omega = 2\pi\nu$$

$$c = \nu\lambda$$

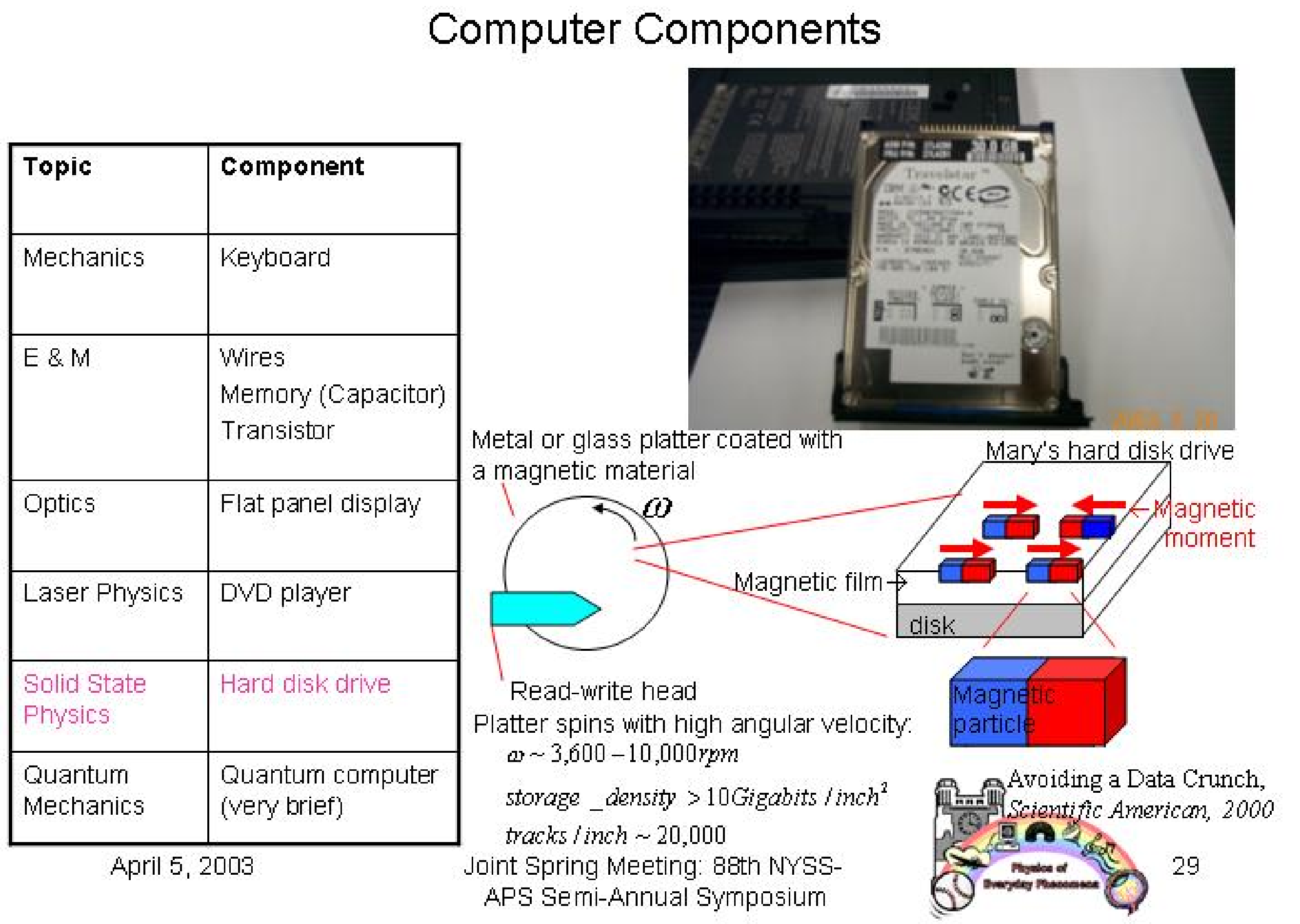
Example: Materials used in lasers are:
- solids (e.g. ruby)
- liquids (e.g. organic dyes)
- gases (e.g. helium-neon, argon)
- semiconductors (e.g., gallium nitride)

April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

Fig. 28. Laser physics: DVD player (the laser).

The term *laser* is a brief description of how laser light is generated - namely, light amplification by stimulated emission of radiation as illustrated in Figure 28. Laser light is generated from a whole host of materials shown here - solids, liquids, gases, semiconductors - when electrons in an excited state of an atom or molecule are encouraged to emit energy as light. This light has certain desirable properties: it’s monochromatic (one color), coherent (in phase), and directional.



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Metal or glass platter coated with a magnetic material

ω

Mary's hard disk drive

Magnetic moment

Magnetic film

disk

Read-write head

Magnetic particle

Platter spins with high angular velocity:

$\omega \sim 3{,}600 - 10{,}000 rpm$

$storage\_density > 10 Gigabits / inch^2$

$tracks / inch \sim 20{,}000$

Avoiding a Data Crunch, *Scientific American, 2000*

April 5, 2003

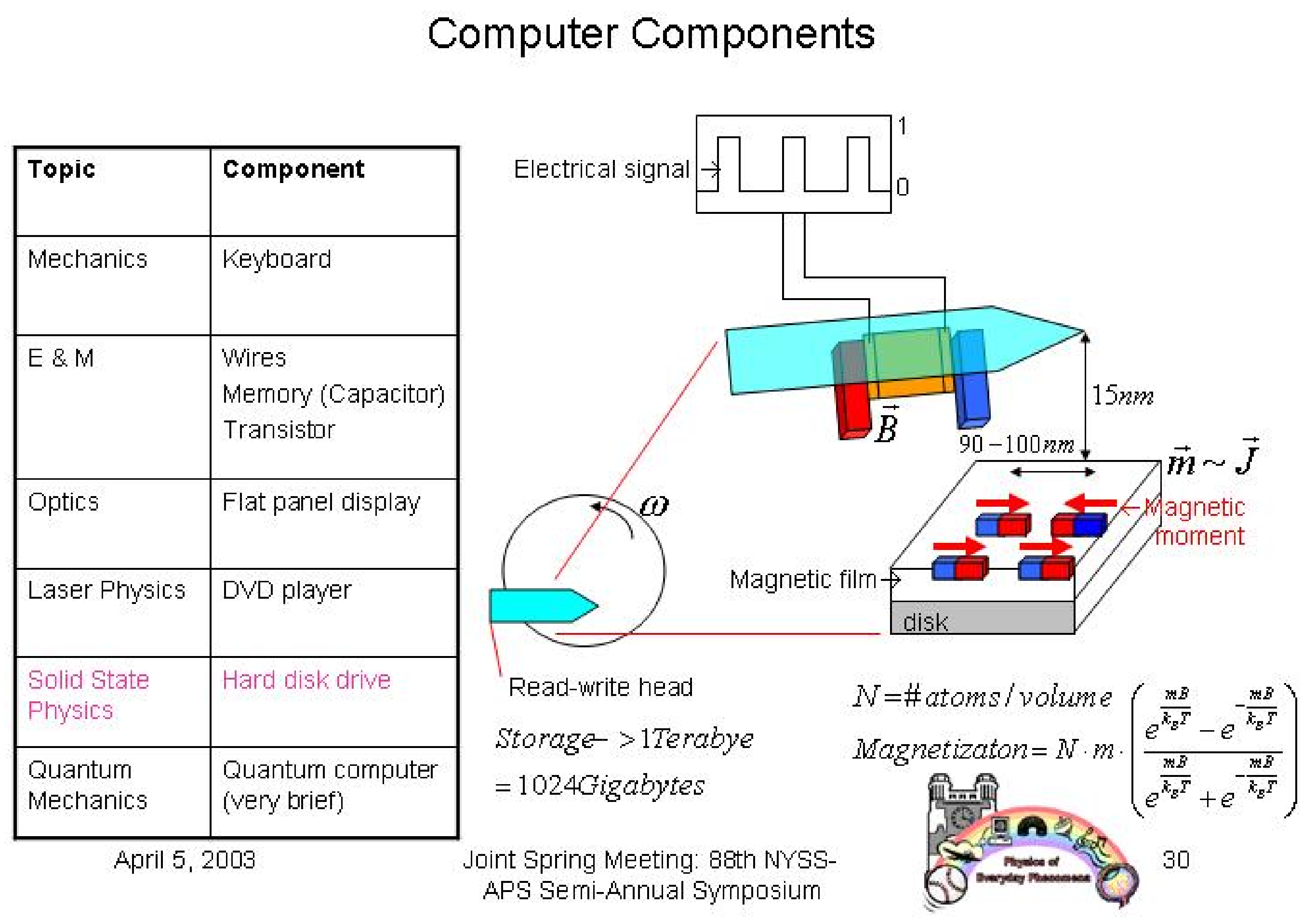
Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

29

Fig. 29. Solid-state physics: Hard disk drive.

X. SOLID STATE PHYSICS: HARD DISK DRIVE

A hard disk is another type of component that allows us to store all our information in the computer, at densities up to 10 Gigabits per square inch. As shown in Figure 29, hard disks are composed of a stack of round platters, either metal or glass, coated with a magnetic material. This is similar to a stack of blueberry pancakes, where the blueberries are really small and scattered on the top of the pancakes. In the hard disk, the platters spin with angular velocity ω between $2,600$ and $10,000$ revolutions per minute, and the data is accessed by read-write heads that fly a few nanometers above the surface which at work they say is similar to the challenge of flying a 747 airplane a few feet above the ground. The density of tracks is on the order of $20,000$ tracks per inch.



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

$Storage– > 1 Terabye$
$= 1024 Gigabytes$

$N = \# atoms / volume$

$$Magnetizaton = N \cdot m \cdot \left(\frac{e^{\frac{mB}{k_B T}} - e^{-\frac{mB}{k_B T}}}{e^{\frac{mB}{k_B T}} + e^{-\frac{mB}{k_B T}}} \right)$$

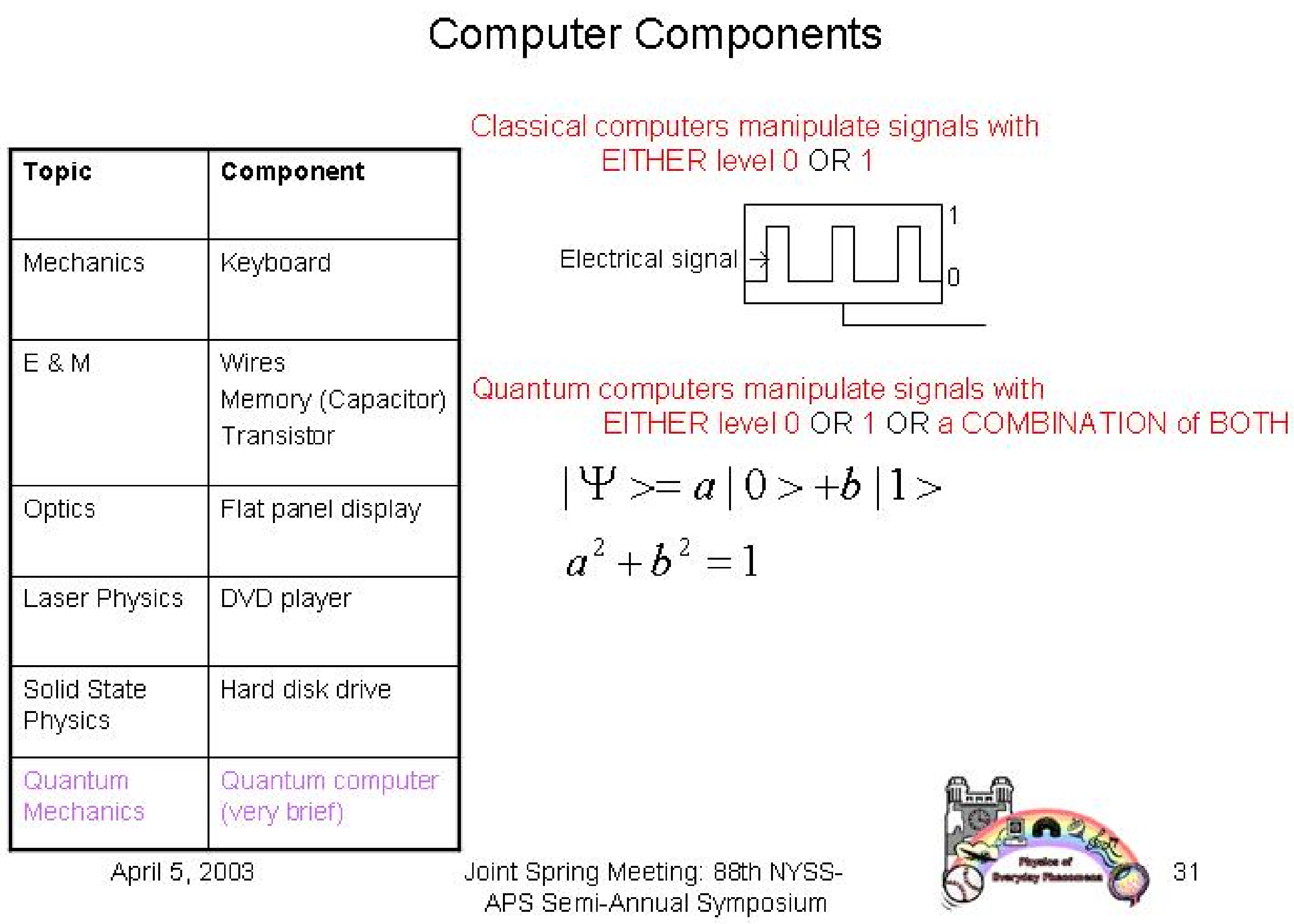
April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

30

Fig. 30. Solid-state physics: Hard disk drive (continued).

A closer look at the magnetic read-write head in Figure 30 shows an old-style pickup coil that reads the magnetic data, where the signal is proportional to the time rate of change of the magnetic flux through the pickup coil (Faraday’s Law). Newer magnetoresistive drive heads read the actual strength of the magnetic field, not the rate at which it is changing.



Computer Components

Topic	Component
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Classical computers manipulate signals with EITHER level 0 OR 1

Quantum computers manipulate signals with EITHER level 0 OR 1 OR a COMBINATION of BOTH

$$|\Psi> = a|0> + b|1>$$

$$a^2 + b^2 = 1$$

April 5, 2003

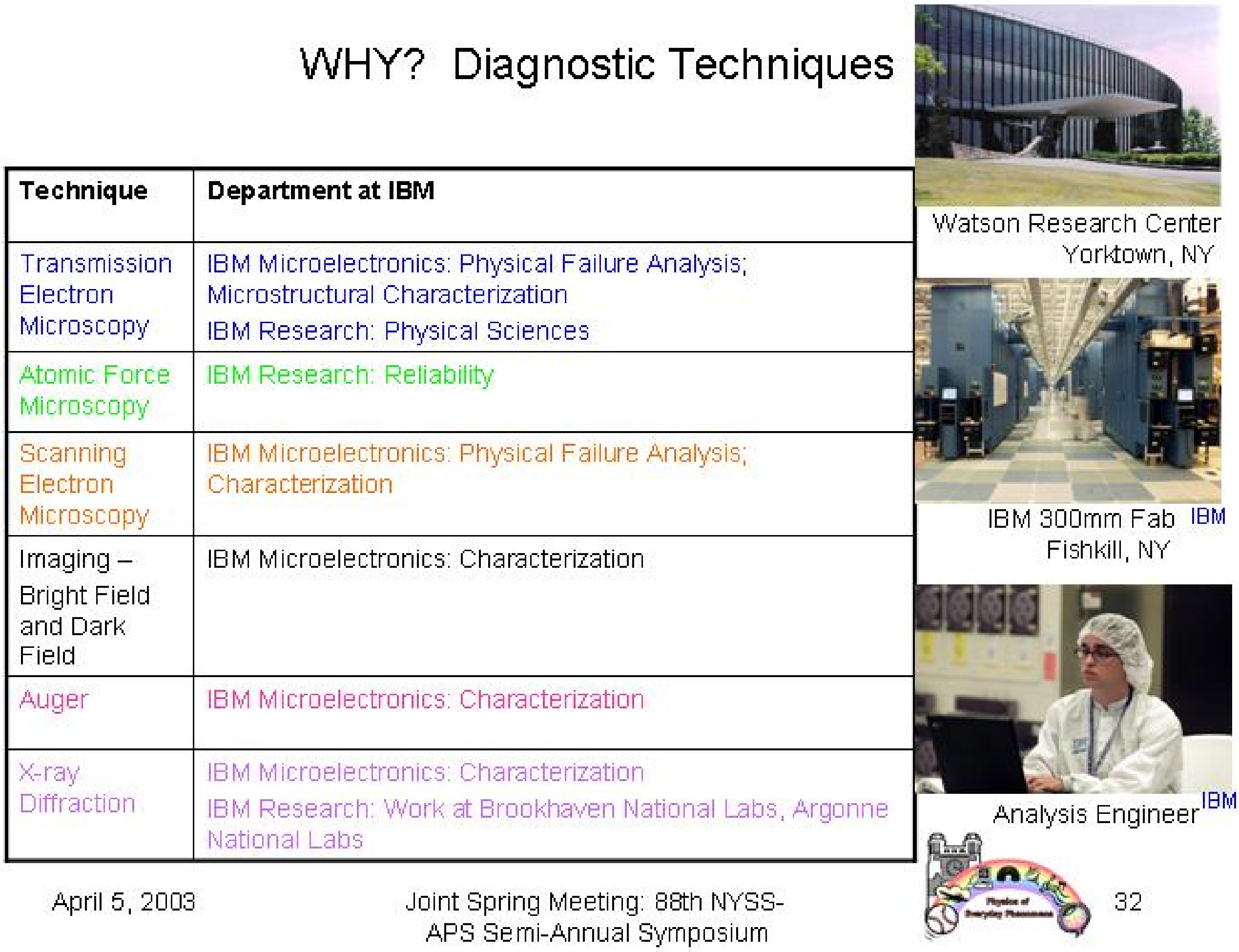
Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

31

Fig. 31. Quantum mechanics: Quantum computer (very brief).

XI. QUANTUM MECHANICS: QUANTUM COMPUTER (VERY BRIEF)

In this talk, we've seen examples of components in which signals are manipulated between the values of zero and one (where one describes the upper switching voltage such as 1.8 Volts). There is a whole new field concerned with developing quantum computers in which the state can be in a combination or superposition of two quantum states as shown in Figure 31. The physics involved in generating these states, manipulating the atoms, and doing computations, is very sophisticated.



WHY? Diagnostic Techniques

Technique	**Department at IBM**
Transmission Electron Microscopy	IBM Microelectronics: Physical Failure Analysis; Microstructural Characterization IBM Research: Physical Sciences
Atomic Force Microscopy	IBM Research: Reliability
Scanning Electron Microscopy	IBM Microelectronics: Physical Failure Analysis; Characterization
Imaging – Bright Field and Dark Field	IBM Microelectronics: Characterization
Auger	IBM Microelectronics: Characterization
X-ray Diffraction	IBM Microelectronics: Characterization IBM Research: Work at Brookhaven National Labs, Argonne National Labs

Watson Research Center
Yorktown, NY

IBM 300mm Fab IBM
Fishkill, NY

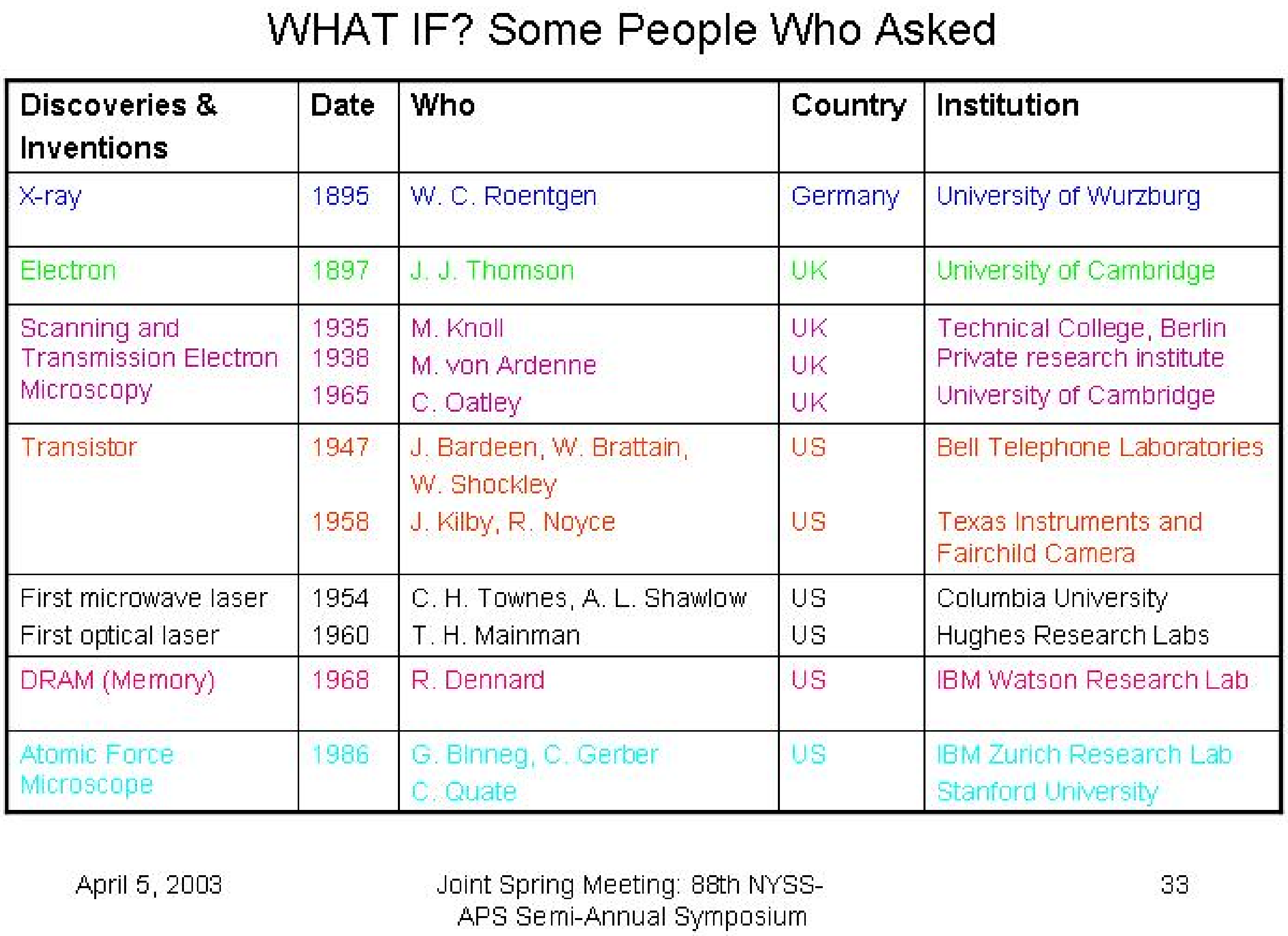
Analysis Engineer IBM

April 5, 2003 Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium 32

Fig. 32. WHY? Some Diagnostic Techniques used at IBM.

XII. WHY? DIAGNOSTIC TECHNIQUES

Now I’d like to discuss where students of physics who specialize in different techniques are employed at IBM, as listed in the table shown in Figure 32. Some of these disciplines, such as scanning electron microscopy and transmission electron microscopy, are important for obtaining the images shown in this talk. Other techniques help us understand device operation or to detect problems in the devices and wires before they are completely manufactured.



WHAT IF? Some People Who Asked

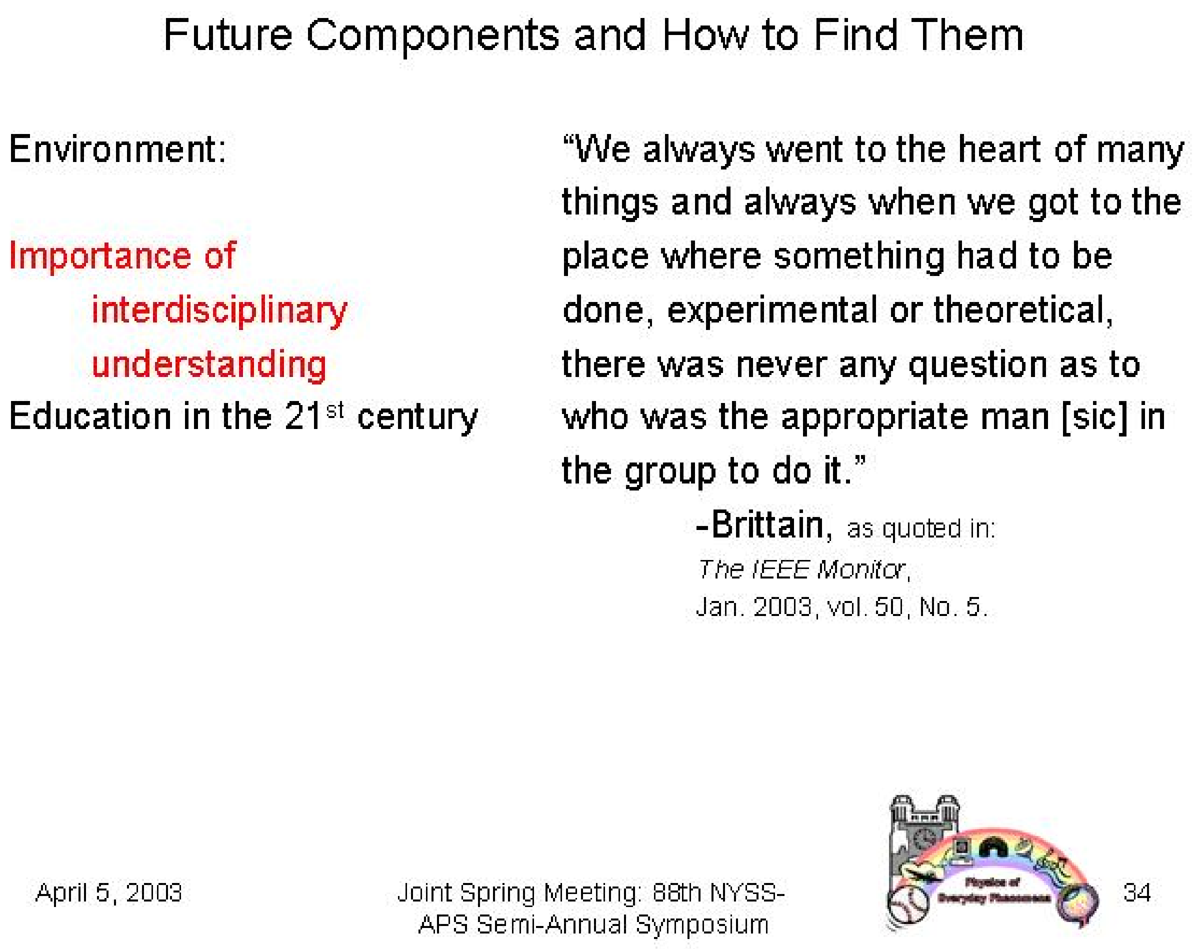
Discoveries & Inventions	Date	Who	Country	Institution
X-ray	1895	W. C. Roentgen	Germany	University of Wurzburg
Electron	1897	J. J. Thomson	UK	University of Cambridge
Scanning and Transmission Electron Microscopy	1935 1938 1965	M. Knoll M. von Ardenne C. Oatley	UK UK UK	Technical College, Berlin Private research institute University of Cambridge
Transistor	1947 1958	J. Bardeen, W. Brattain, W. Shockley J. Kilby, R. Noyce	US US	Bell Telephone Laboratories Texas Instruments and Fairchild Camera
First microwave laser First optical laser	1954 1960	C. H. Townes, A. L. Shawlow T. H. Mainman	US US	Columbia University Hughes Research Labs
DRAM (Memory)	1968	R. Dennard	US	IBM Watson Research Lab
Atomic Force Microscope	1986	G. Binneg, C. Gerber C. Quate	US	IBM Zurich Research Lab Stanford University

April 5, 2003 Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium 33

Fig. 33. WHAT IF? Some people who asked.

XIII. WHAT IF? SOME PEOPLE WHO ASKED

In the table in Figure 33 I simply list some people without whom the tremendous advance in computer components simply would not have been able to happen. It gives us some perspective on the history of our field, that physics and the understanding of the basics can have had such a great impact.



Future Components and How to Find Them

Environment:

Importance of
interdisciplinary
understanding

Education in the 21st century

"We always went to the heart of many things and always when we got to the place where something had to be done, experimental or theoretical, there was never any question as to who was the appropriate man [sic] in the group to do it."

-**Brittain**, as quoted in:
The IEEE Monitor,
Jan. 2003, vol. 50, No. 5.

April 5, 2003

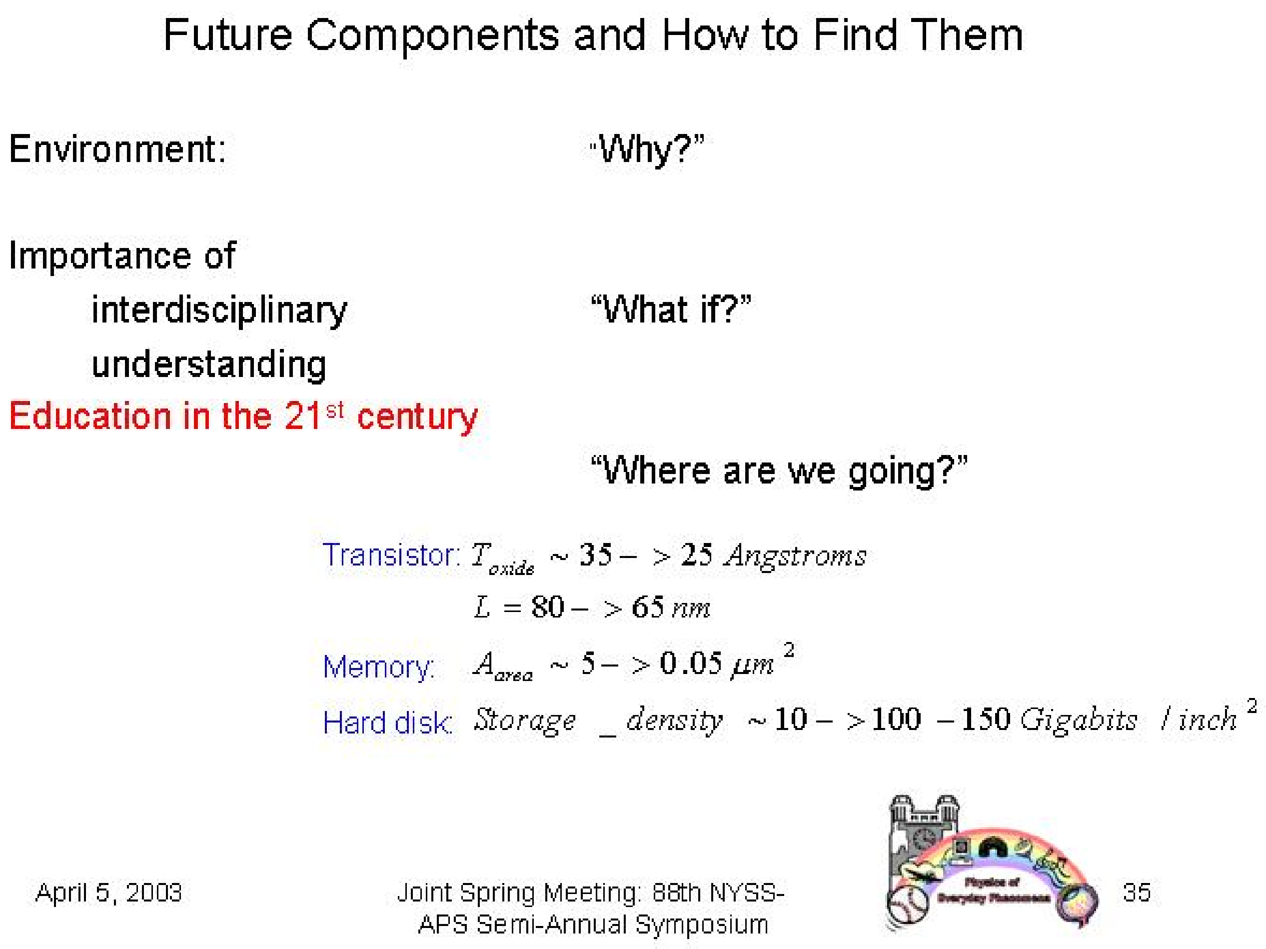
Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

34

Fig. 34. Future components and how to find them: Importance of interdisciplinary understanding.

XIV. FUTURE COMPONENTS AND HOW TO FIND THEM

So how do we find future components? We have to be able to answer the questions: "What are we doing?" "Why are we doing it?" "Who cares?" "How much will it cost?" "How long will it take?" Here's one answer by one of the inventors of the transistor. He says, "We always went to the heart of many things, and always when we got to the place where something had to be done...there was never any question" as to whom should do it. This quote is shown in Figure 34.



Future Components and How to Find Them

Environment: "Why?"

Importance of interdisciplinary understanding "What if?"

Education in the 21st century

"Where are we going?"

Transistor: $T_{oxide} \sim 35 -> 25\ Angstroms$

$L = 80 -> 65\ nm$

Memory: $A_{area} \sim 5 -> 0.05\ \mu m^2$

Hard disk: $Storage\_density \sim 10 -> 100 - 150\ Gigabits / inch^2$

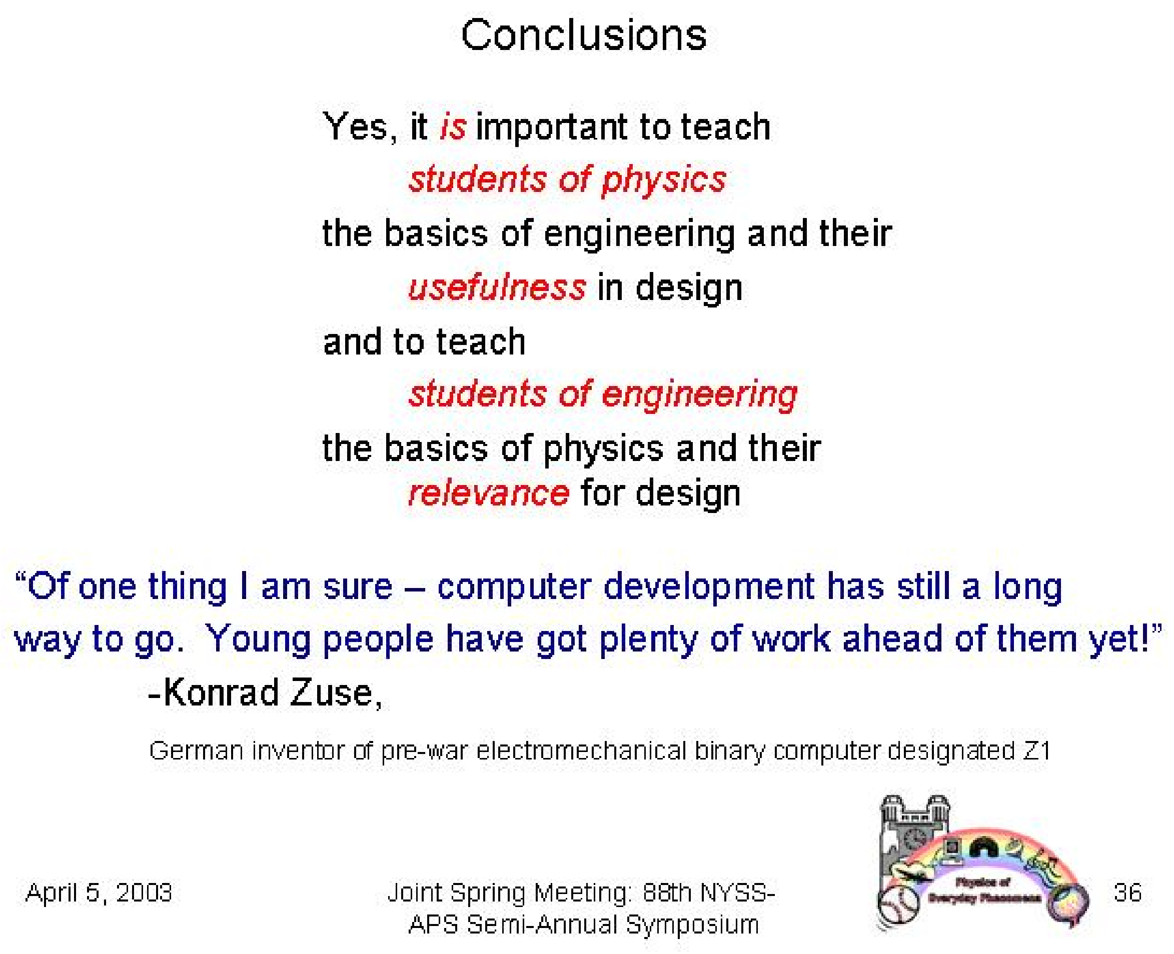
April 5, 2003

Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium

35

Fig. 35. Future components and how to find them: Education in the 21st century.

So we ask in our case, as shown in Figure 35. Where is the development of computer components going, and do I want to be a part of it? Transistors are shrinking: When will the classical transistor become too unwieldy? Memory capacitors are shrinking: They are becoming 100 times smaller. Hard disks are expanding a factor of 10 as their bit densities continue to rise. Each field has challenges, and some are inherent in the physics of the materials, and some are provided by the design constraints.



Conclusions

Yes, it *is* important to teach
students of physics
the basics of engineering and their
usefulness in design
and to teach
students of engineering
the basics of physics and their
relevance for design

"Of one thing I am sure – computer development has still a long way to go. Young people have got plenty of work ahead of them yet!"
-Konrad Zuse,
German inventor of pre-war electromechanical binary computer designated Z1

April 5, 2003
Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium
36

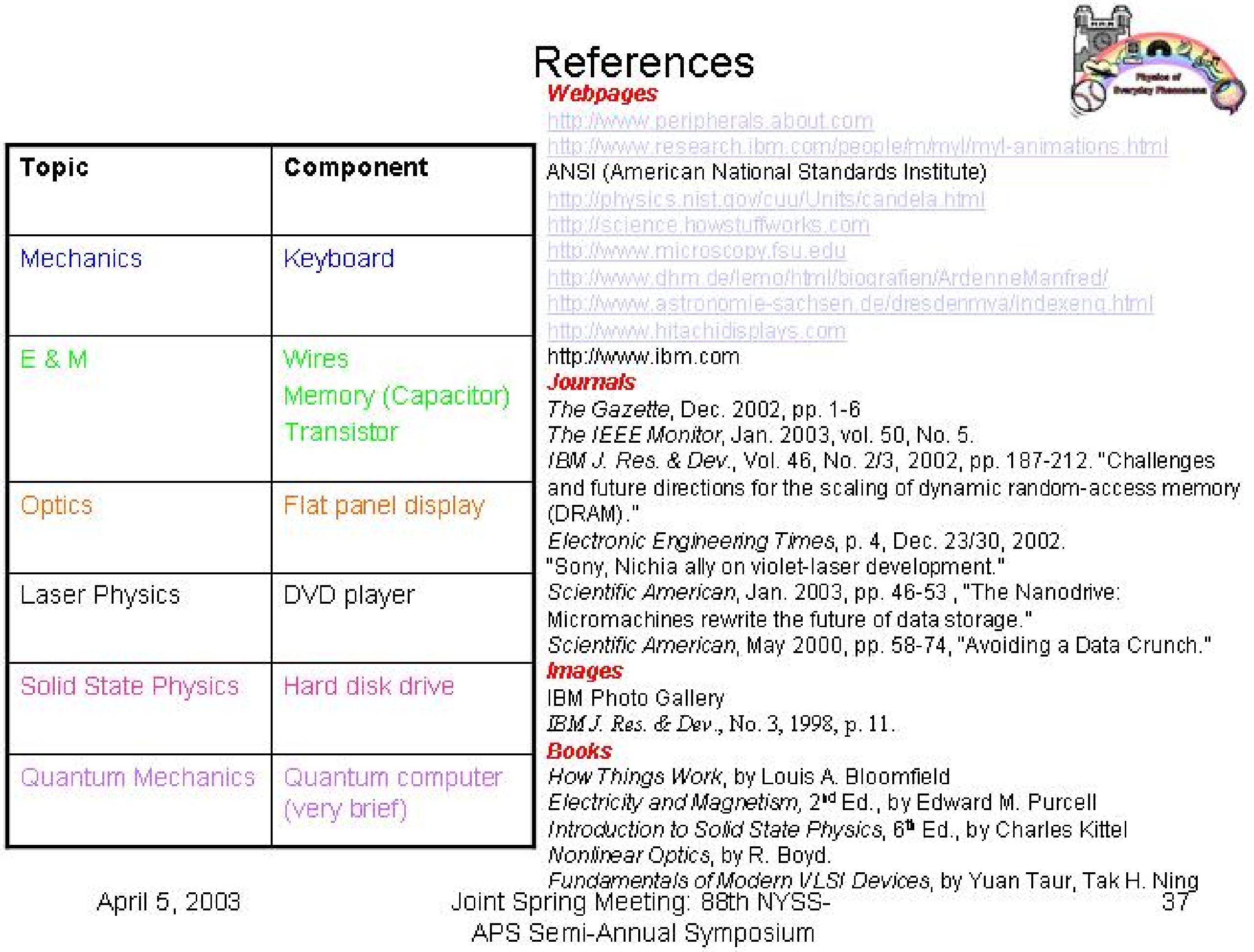
Fig. 36. Conclusions: Yes, it is important to teach students of physics the basics of engineering.

XV. CONCLUSIONS

So we conclude as shown in Figure 36 by answering the question at the beginning, that "YES, it IS important to teach students of physics the basics of engineering and impact of design constraints."

And finally I quote Konrad Zuse who physically built the Z1, a pre-World War II electro-mechanical binary computer. He said, "Of one thing I am sure - computer development has still a long way to go. Young people have got plenty of work ahead of them yet!"

Thank you.



References

Topic	**Component**
Mechanics	Keyboard
E & M	Wires Memory (Capacitor) Transistor
Optics	Flat panel display
Laser Physics	DVD player
Solid State Physics	Hard disk drive
Quantum Mechanics	Quantum computer (very brief)

Webpages

http://www.peripherals.about.com
http://www.research.ibm.com/people/m/myl/myl-animations.html
ANSI (American National Standards Institute)
http://physics.nist.gov/cuu/Units/candela.html
http://science.howstuffworks.com
http://www.microscopy.fsu.edu
http://www.dhm.de/lemo/html/biografien/ArdenneManfred/
http://www.astronomie-sachsen.de/dresdenmva/indexeng.html
http://www.hitachidisplays.com
http://www.ibm.com

Journals

The Gazette, Dec. 2002, pp. 1-6
The IEEE Monitor, Jan. 2003, vol. 50, No. 5.
IBM J. Res. & Dev., Vol. 46, No. 2/3, 2002, pp. 187-212. "Challenges and future directions for the scaling of dynamic random-access memory (DRAM)."
Electronic Engineering Times, p. 4, Dec. 23/30, 2002. "Sony, Nichia ally on violet-laser development."
Scientific American, Jan. 2003, pp. 46-53 , "The Nanodrive: Micromachines rewrite the future of data storage."
Scientific American, May 2000, pp. 58-74, "Avoiding a Data Crunch."

Images

IBM Photo Gallery
IBM J. Res. & Dev., No. 3, 1998, p. 11.

Books

How Things Work, by Louis A. Bloomfield
Electricity and Magnetism, 2nd Ed., by Edward M. Purcell
Introduction to Solid State Physics, 6th Ed., by Charles Kittel
Nonlinear Optics, by R. Boyd.
Fundamentals of Modern VLSI Devices, by Yuan Taur, Tak H. Ning

April 5, 2003
Joint Spring Meeting: 88th NYSS-APS Semi-Annual Symposium
37

Fig. 37. References.

XVI. REFERENCES

References used in this talk are indicated on each figure and on the summary of References in Figure 37.

REFERENCES

[1] http://www.peripherals.about.com.
[2] http://www.research.ibm.com/people/m/myl/myl-animations.html
[3] ANSI (American National Standards Institute)
[4] http://physics.nist.gov/cuu/Units/candela.html
[5] http://science.howstuffworks.com
[6] http://www.microscopy.fsu.edu
[7] http://www.dhm.de/lemo/html/biografien/ArdenneManfred/
[8] http://www.astronomie-sachsen.de/dresdenmva/indexeng.html
[9] http://www.hitachidisplays.com
[10] http://www.ibm.com
[11] *The Gazette*, December 2002, pp. 1-6.
[12] *The IEEE Monitor*, January 2003, vol. 50, No. 5.
[13] “Challenges and future directions for the scaling of dynamic random-access memory (DRAM)” in *IBM J. Res. and Dev.*, Vol. 46, No. 2/3, 2002, pp. 187-212.
[14] “Sony, Nichia ally on violet-laser development,”, in *Electronic Engineering Times*, December 23/30, 2002, p. 4.
[15] “The Nanodrive: Micromachines rewrite the future of data storage,” in *Scientific American*, January 2003, pp. 46-53.
[16] “Avoiding a Data Crunch,” in *Scientific American*, May 2000, pp. 58-74.
[17] IBM Photo Gallery.
[18] IBM J. Res. and Dev., No. 3, 1999, p. 11.

[19] Louis A. Bloomfield, *How Things Work*.
[20] Edward M. Purcell, *Electricity and Magnetism, 2nd Edition*.
[21] Charles Kittel, *Introduction to Solid State Physics, 6th Edition*.
[22] Robert Boyd, *Nonlinear Optics*.
[23] Yuan Taur and Tak. H. Ning, *Fundamentals of Modern VLSI Devices*.