# Biomedical physics for undergraduate STEM majors

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- Professor of Physics
- Loyola University Maryland

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- Thank you, Mariel Meier, Oglethorpe Univ; Nancy Donaldson, Rockhurst Univ

Winter 2022 AAPT meeting

# Context

- Loyola is a private, comprehensive, liberal arts university
- Physics department only teaches undergraduate courses
- Traditional physics program. Physics majors go to graduate school (mostly physics) or become employed.
- Number of physics majors is small.
- We considered ways of bringing students outside of physics into physics courses.
- Led to development of a biomedical physics minor, administered by the physics department.

# Biomedical physics minor

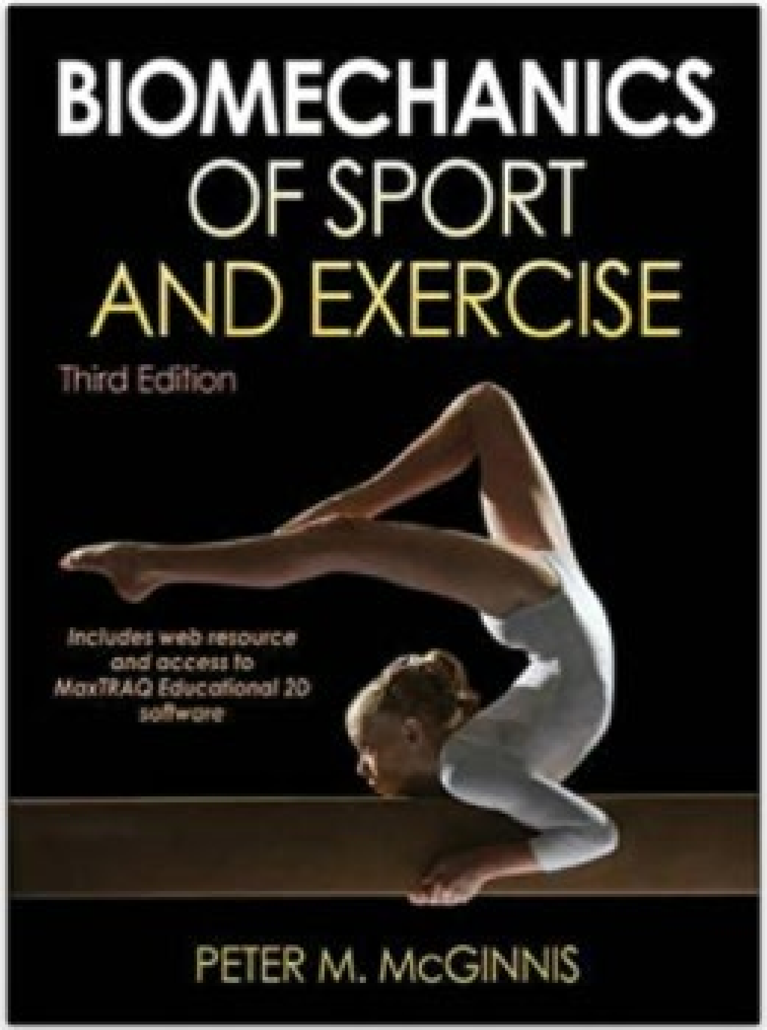
- Comprised of seven courses. Most students take the following:
  - General Physics II (intro, calc-based physics, Gen Physics I is required also)
  - Calculus I
  - At least one majors-level course in biology or chemistry
  - Physics of medicine and the human body, i.e. biomechanics
  - Waves and the physics of medicine, i.e. diagnostic and therapeutic methods in medicine
  - Project or research course relevant to biomedical sciences
  - STEM course that does not count towards the major (there is a list of approved courses)

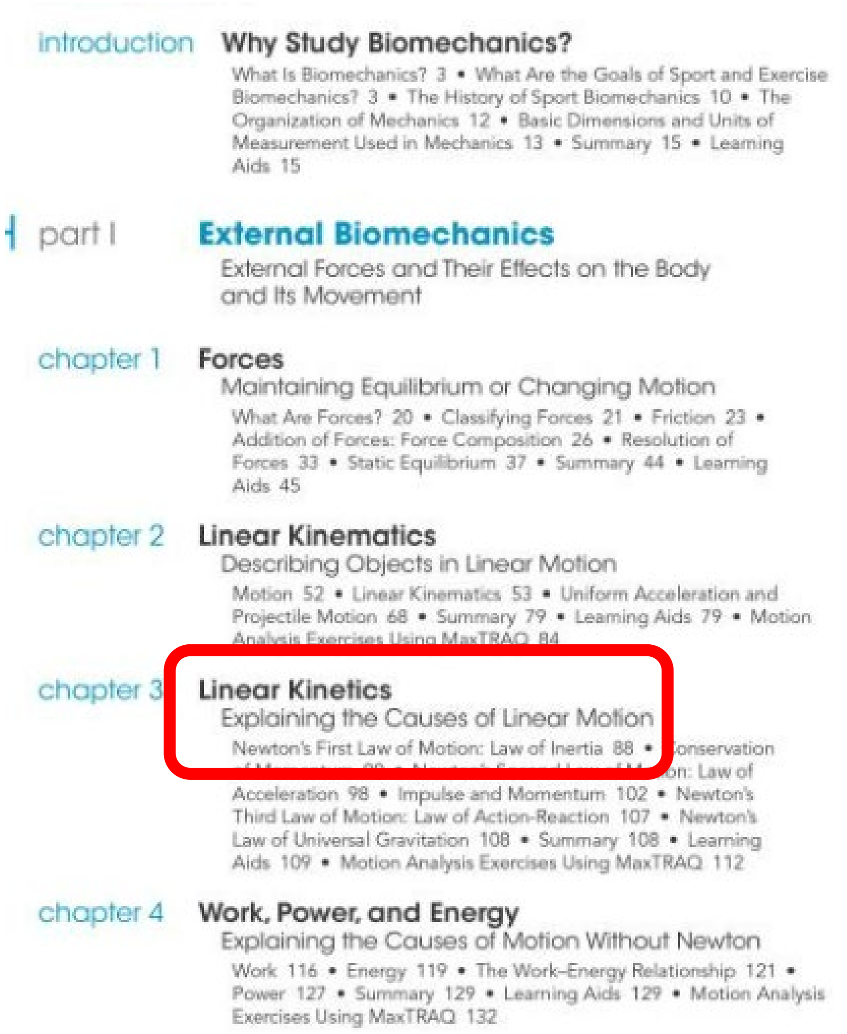
# Teaching approach

The remainder of this talk will survey the activities in the physics of medicine courses.

- Students have had 0.5 - 3.5 years of physics.
- Traditional aspects
  - Textbook(s) provides framework
  - Homework problems
  - Lecture
  - Tests
- Not-traditional aspects
  - In-class activities. Supplement text with my own writeups.
  - In a typical time slot (50-75 min), analysis may have to be completed as homework.
  - Reading. Large amount of factual info. Important for synthesis with other courses and their own experiences about their bodies.
  - Short project where they research a topic and present a PPT.
  - Field trip

# Biomechanics





introduction **Why Study Biomechanics?**
What Is Biomechanics? 3 • What Are the Goals of Sport and Exercise Biomechanics? 3 • The History of Sport Biomechanics 10 • The Organization of Mechanics 12 • Basic Dimensions and Units of Measurement Used in Mechanics 13 • Summary 15 • Learning Aids 15

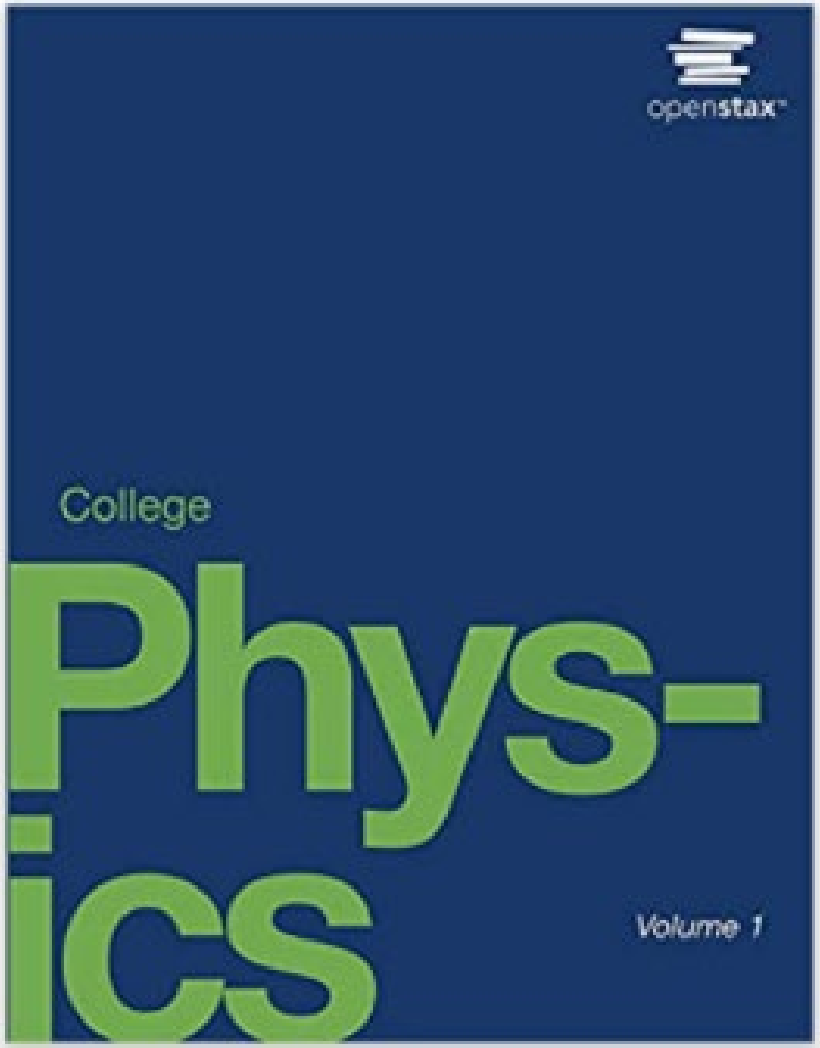
part I **External Biomechanics**
External Forces and Their Effects on the Body and Its Movement

chapter 1 **Forces**
Maintaining Equilibrium or Changing Motion
What Are Forces? 20 • Classifying Forces 21 • Friction 23 • Addition of Forces: Force Composition 26 • Resolution of Forces 33 • Static Equilibrium 37 • Summary 44 • Learning Aids 45

chapter 2 **Linear Kinematics**
Describing Objects in Linear Motion
Motion 52 • Linear Kinematics 53 • Uniform Acceleration and Projectile Motion 68 • Summary 79 • Learning Aids 79 • Motion Analysis Exercises Using MaxTRAQ 84

chapter 3 **Linear Kinetics**
Explaining the Causes of Linear Motion
Newton's First Law of Motion: Law of Inertia 88 • onservation [illegible] on: Law of Acceleration 98 • Impulse and Momentum 102 • Newton's Third Law of Motion: Law of Action-Reaction 107 • Newton's Law of Universal Gravitation 108 • Summary 108 • Learning Aids 109 • Motion Analysis Exercises Using MaxTRAQ 112

chapter 4 **Work, Power, and Energy**
Explaining the Causes of Motion Without Newton
Work 116 • Energy 119 • The Work–Energy Relationship 121 • Power 127 • Summary 129 • Learning Aids 129 • Motion Analysis Exercises Using MaxTRAQ 132

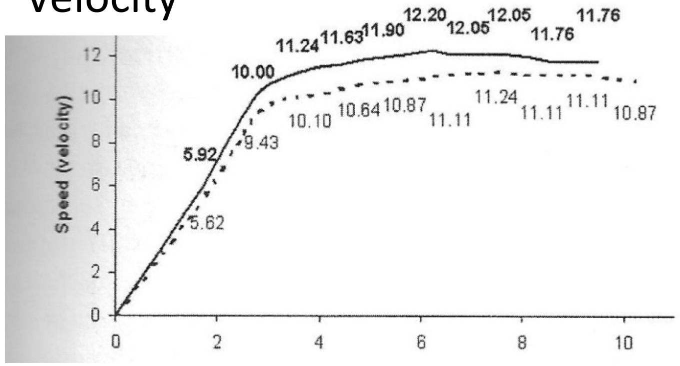


- Students have already had mechanics in an intro physics course. Need to learn how to apply knowledge to the human body.
- Students enjoy reading. Technical writing improves.

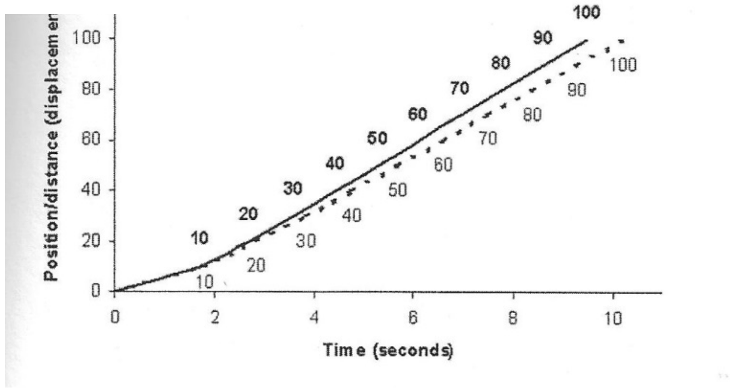
# Linear kinematics

- Excel
- Analyze data
- Compute displacement, velocity, acceleration

Velocity



Position

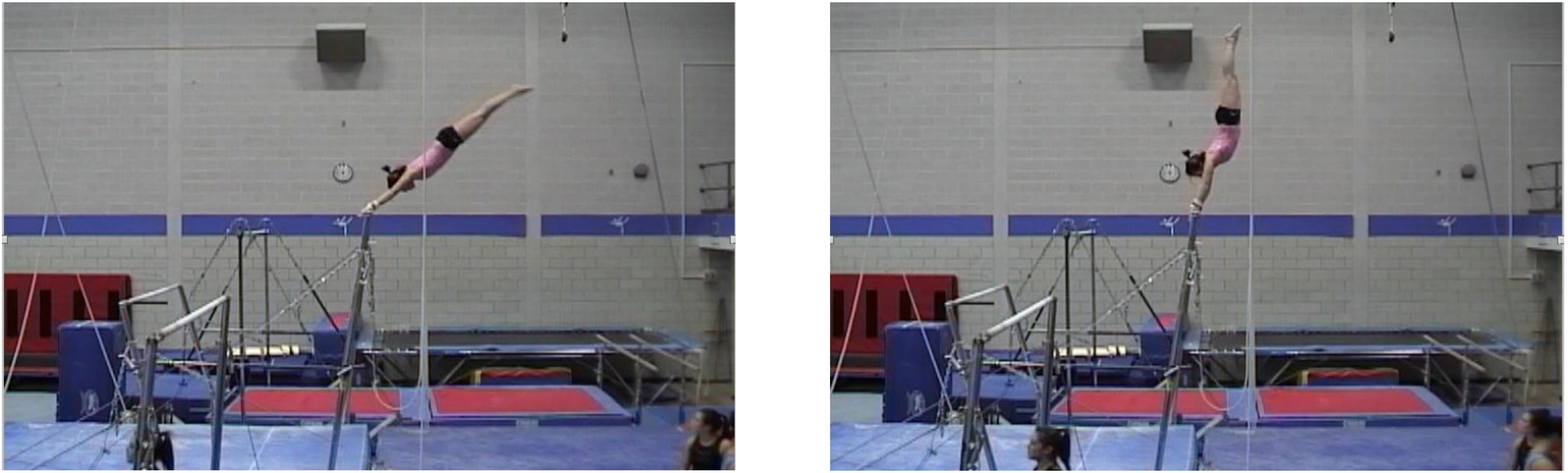


100 m race: solid line – men; dashed line – women

| n | Position (m) | Usain Bolt | Tyson Gay |
|---|---|---|---|
| | | Elapsed time (s) | Elapsed time (s) |
| 0 | 0 | 0 | 0 |
| 1 | 10 | 1.89 | 1.91 |
| 2 | 20 | 2.88 | 2.92 |
| 3 | 30 | 3.78 | 3.83 |
| 4 | 40 | 4.64 | 4.70 |
| 5 | 50 | 5.47 | 5.55 |
| 6 | 60 | 6.29 | 6.39 |
| 7 | 70 | 7.10 | 7.20 |
| 8 | 80 | 7.92 | 8.02 |
| 9 | 90 | 8.75 | 8.86 |
| 10 | 100 | 9.58 | 9.71 |

100 m race: Usain Bolt and Tyson Gay (2009)

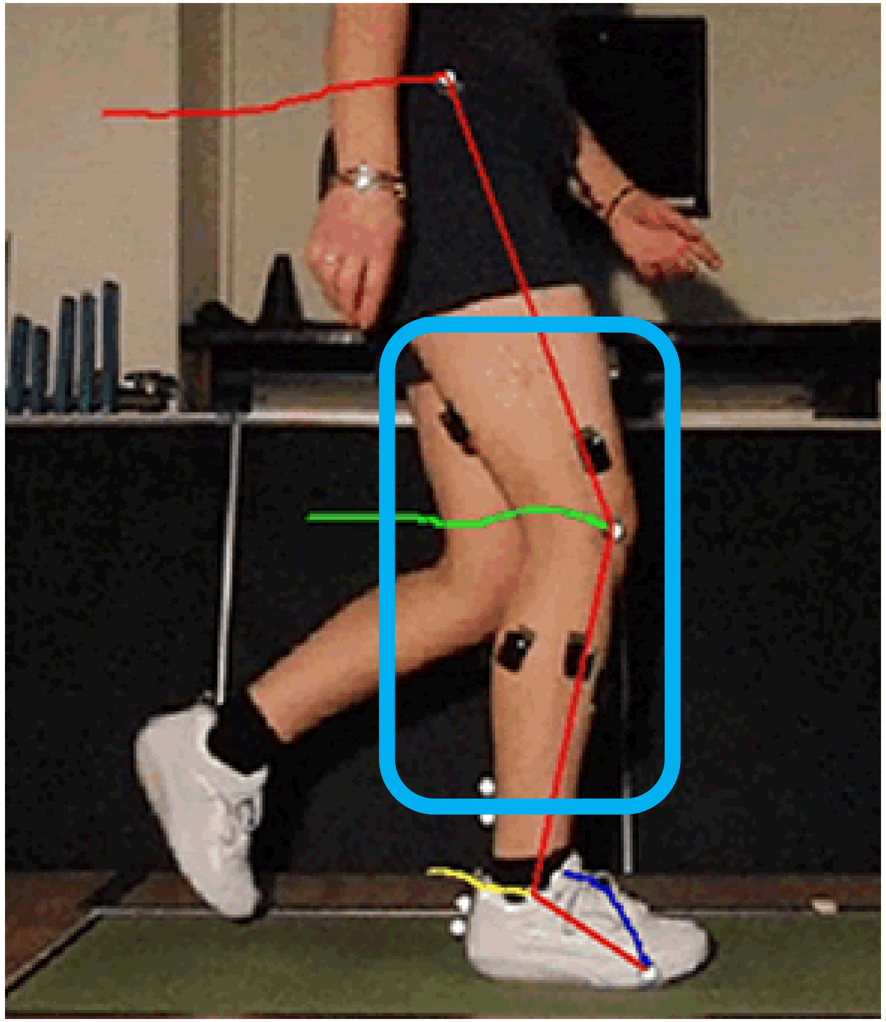
# Video analysis applied to linear and angular motions in sports

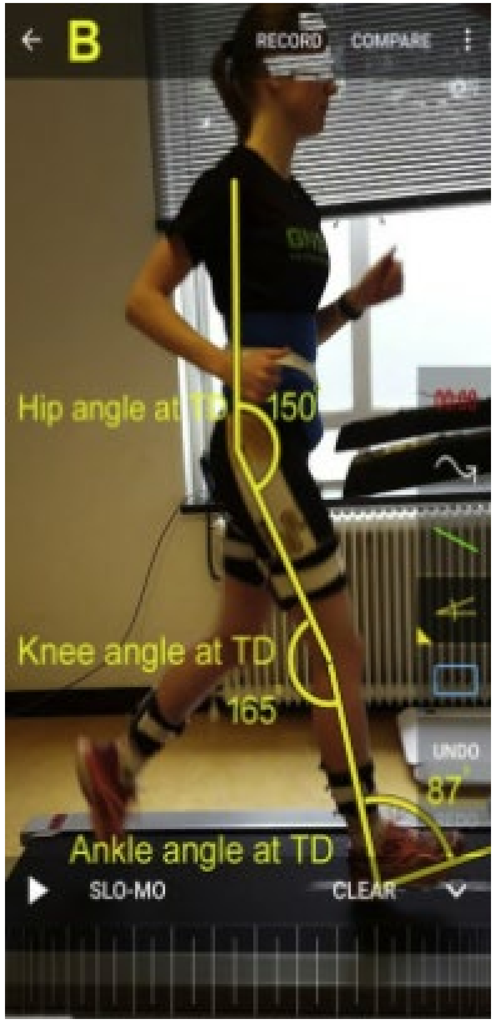


MaxTraq  or Vernier LoggerPro for video analysis

# iPhone video

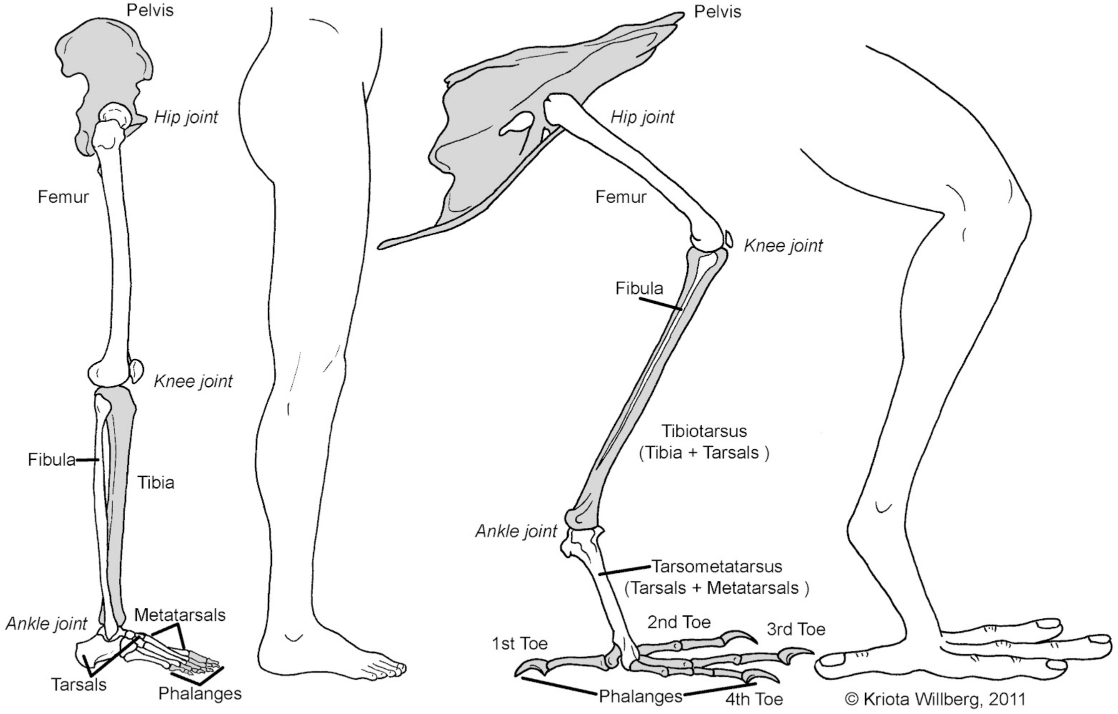
- Markers
- Vernier LoggerPro software
- Excel
- Good for remote learning





# Dissection of chicken quarter

- Helps physics, CS, Eng, math majors understand what makes the body move. Bio and chem majors may have done dissections online or on preserved animals, never on raw meat.
- Rods, plates, ropes, hinges, pulleys



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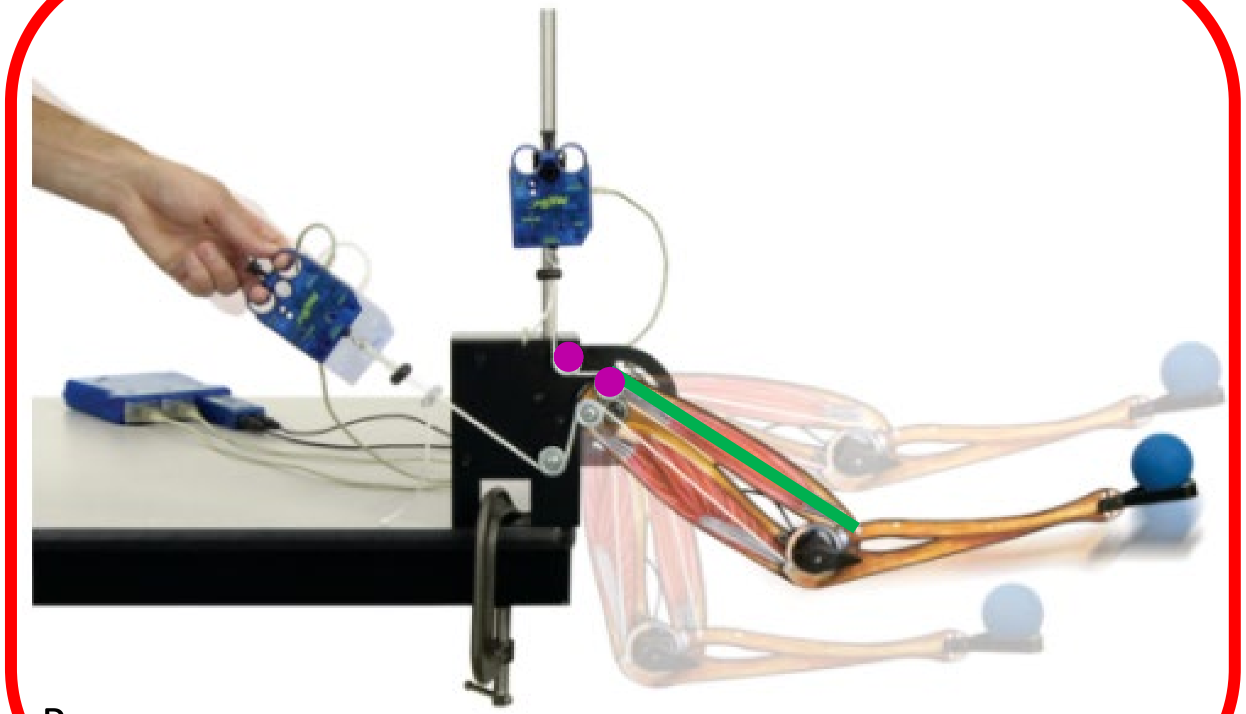
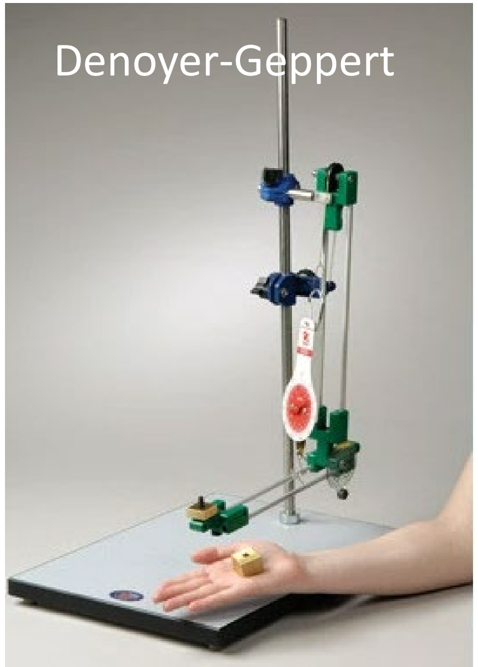
# Arm model

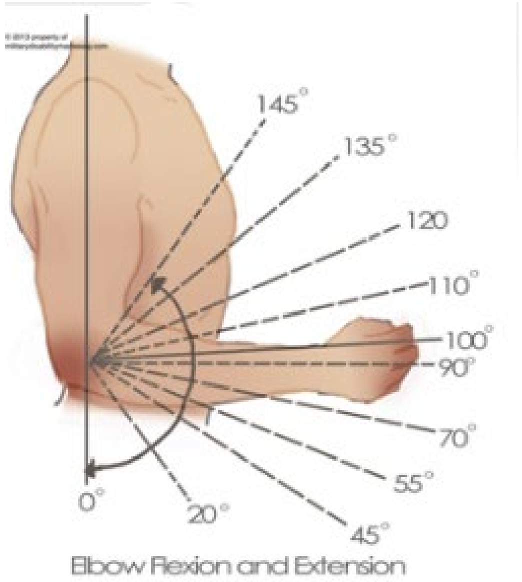
- Start with simple rods and right angle bend at elbow
- Progress to more complex arm with bent elbow. Investigate attachment point of biceps



Pasco



Denoyer-Geppert



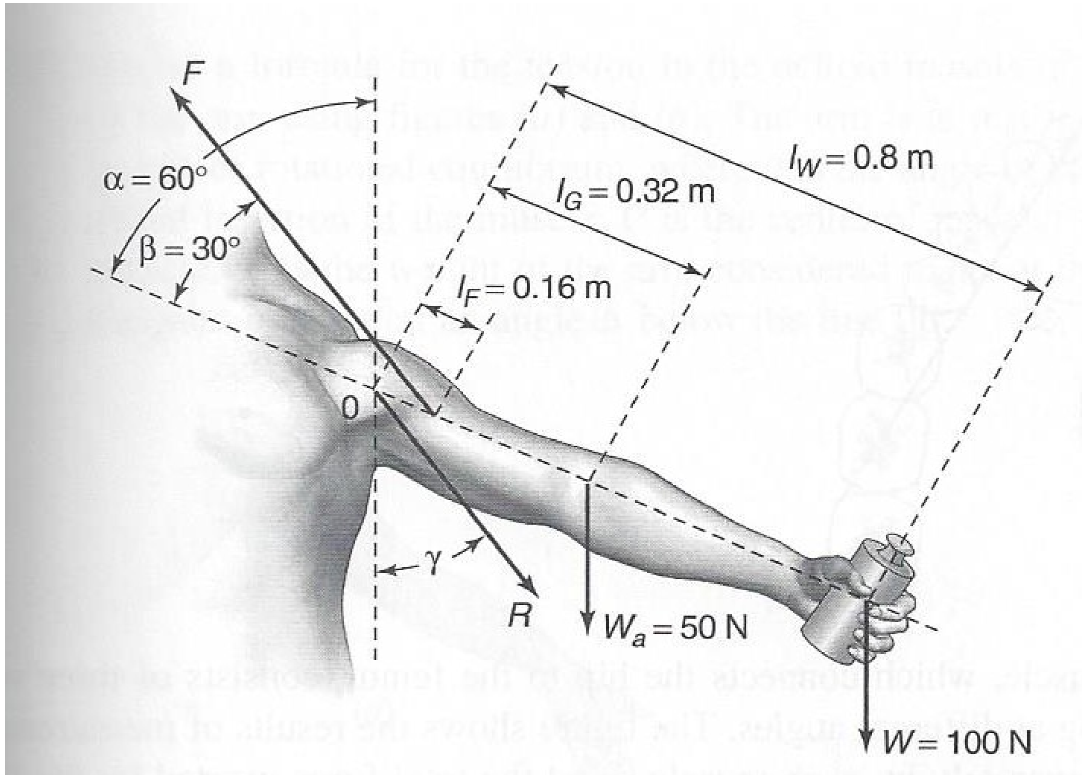
# Gastrocnemius (calf muscle) and foot model

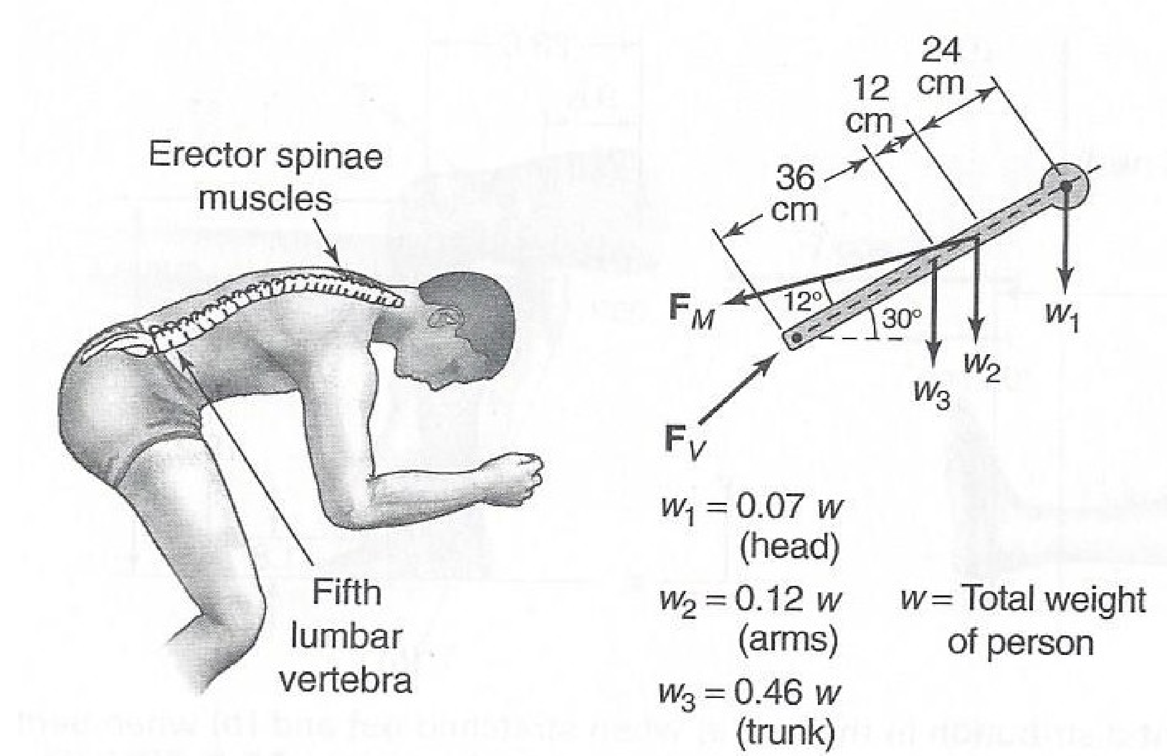
- Compare arm and foot lever systems

Denoyer-Geppert

# Force and torque problems

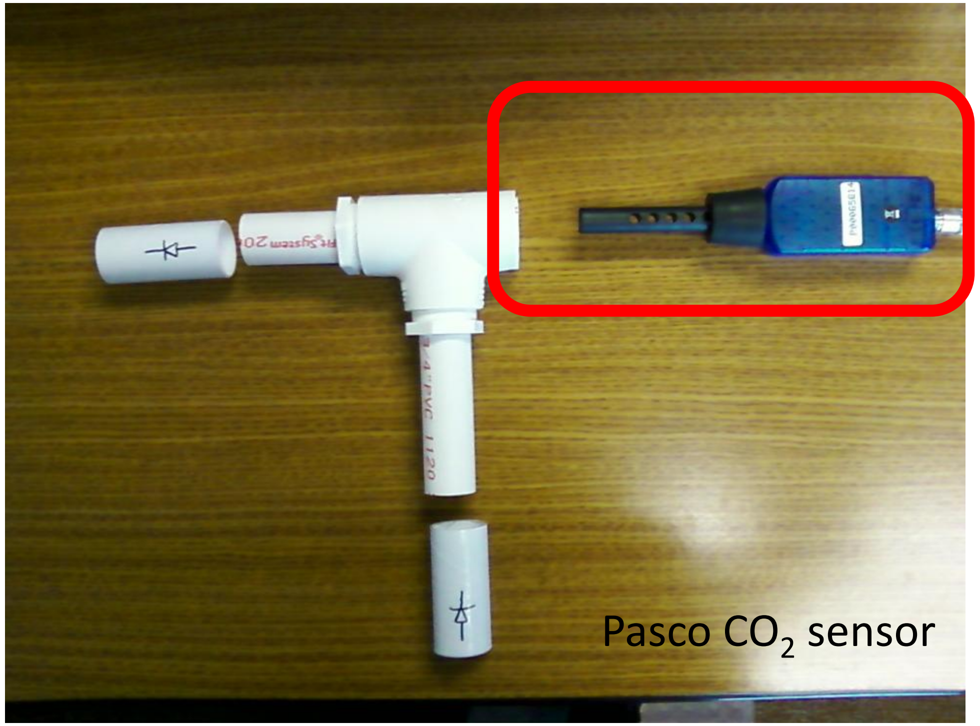
- Deltoid, back, neck, head, jaw, etc.
- Tuszynski and Dixon, “Biomed. Appl. Intro Physics,” has a wealth of problems.





# Work, energy, power, metabolic efficiency

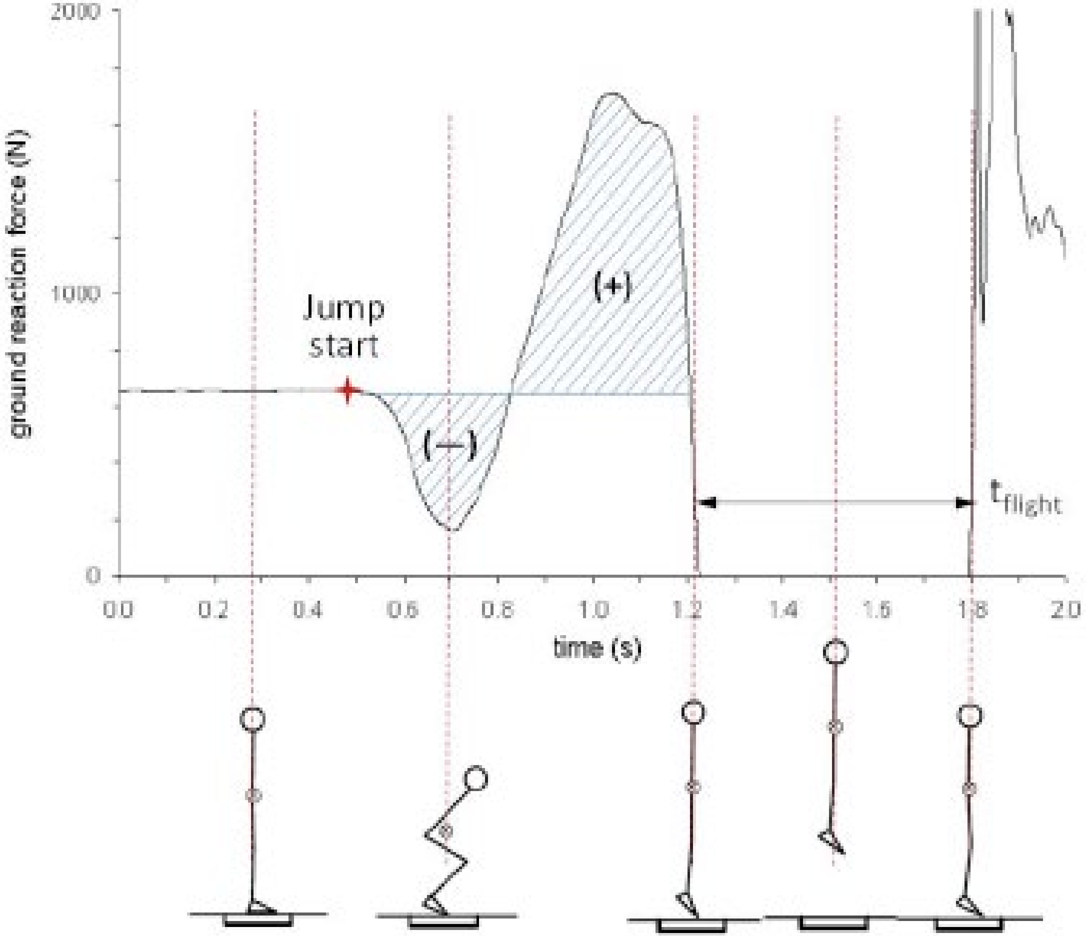
- Measure $CO_2$ before and after aerobic exercise.
- Adapted from writeup by Gabriela Waschewsky



Pasco $CO_2$ sensor

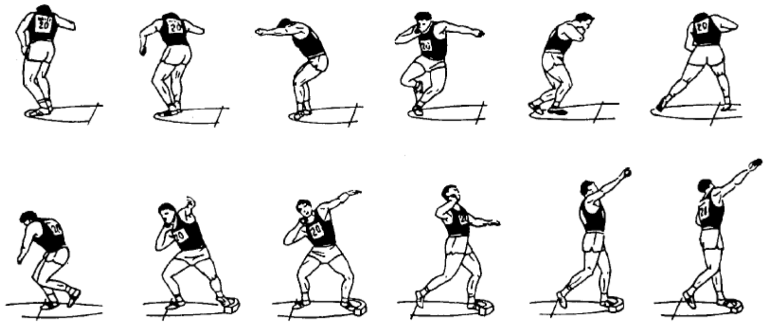
# Jumping on a force plate

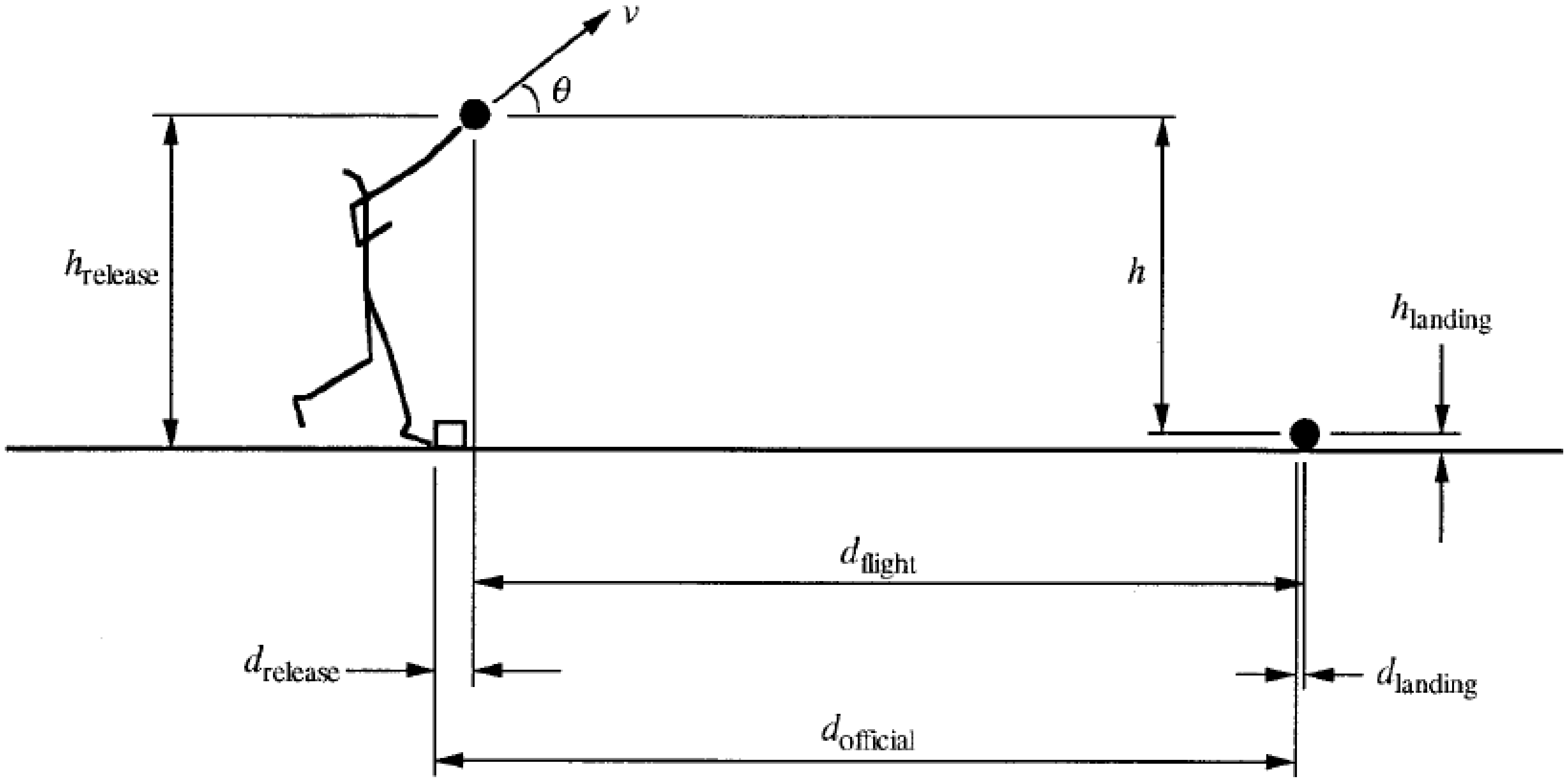
- Force, impulse, momentum, energy
- Graphing, integration
- Modeling



# Modeling: Soccer throw-in or launch of shot put

- Extension of projectile problem to include human body
- Modeling (Linthorne papers)
- Use Excel, Mathematica, Matlab or write code

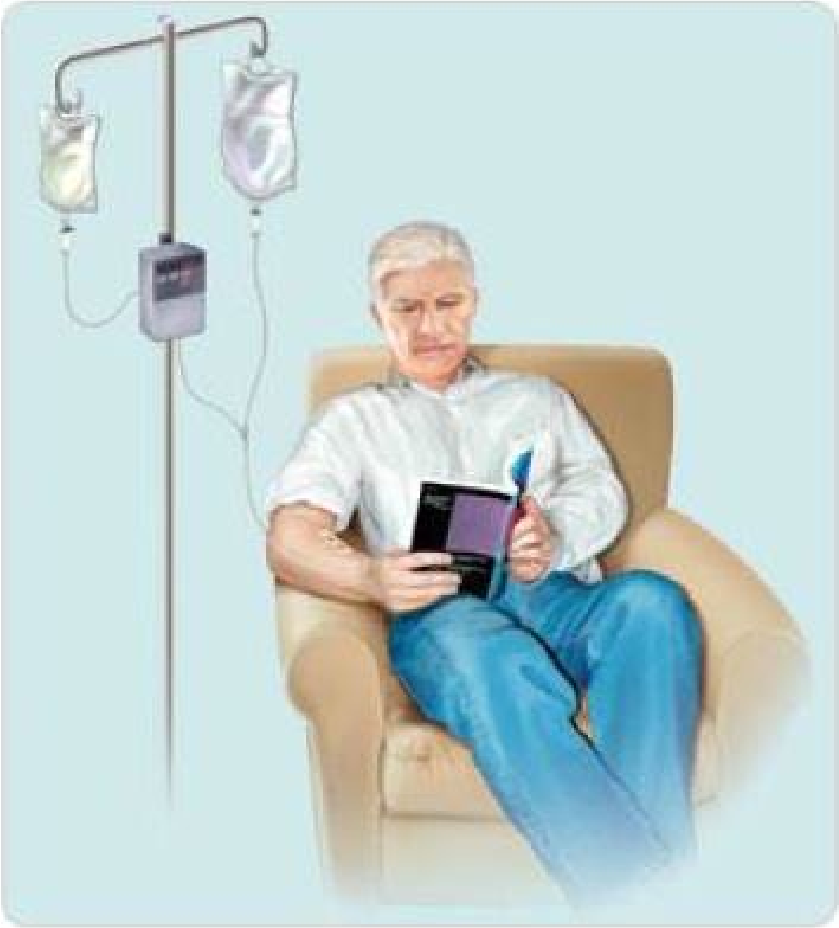




# Fluid mechanics

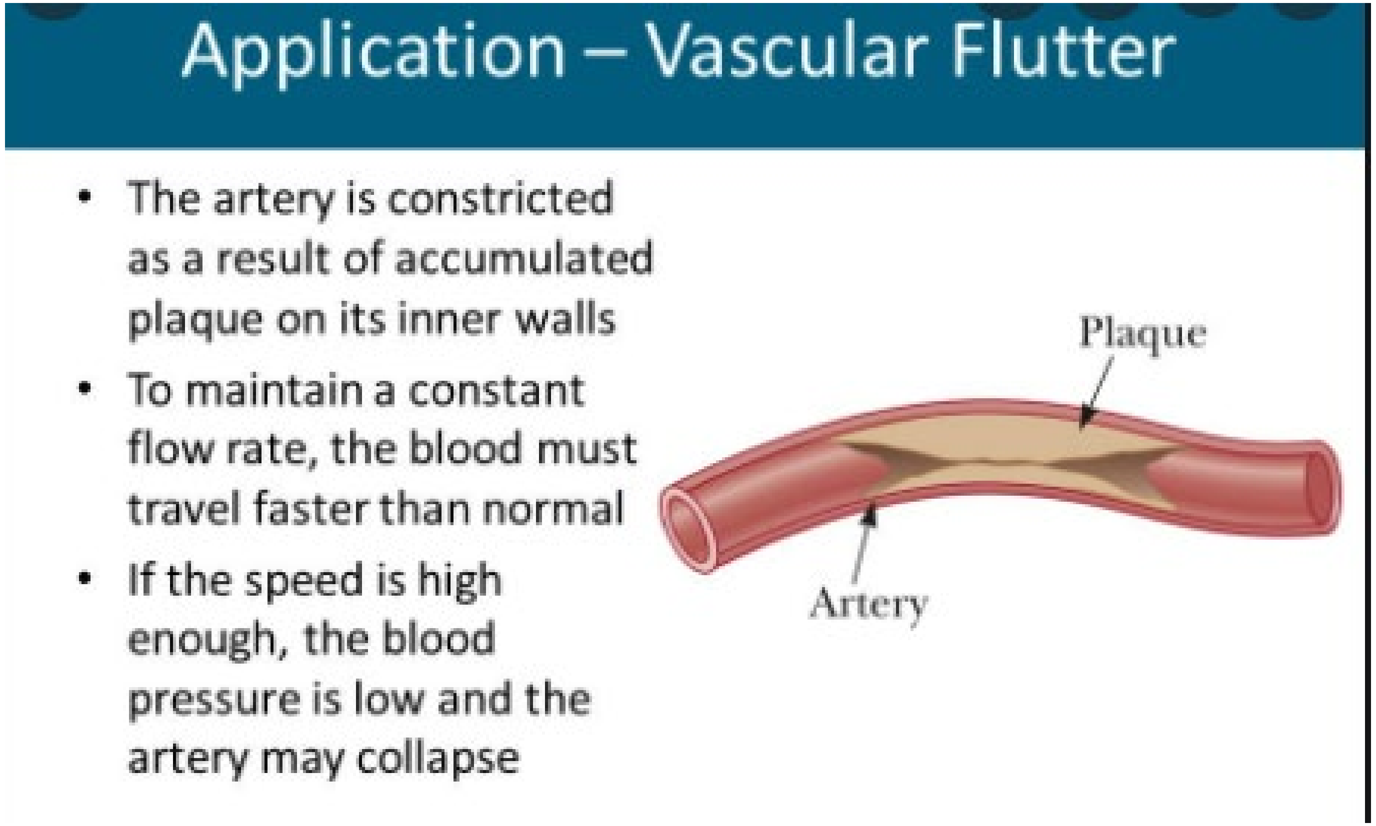
- I prefer standard intro physics textbook
- Hydrostatics and hydrodynamics
- Examples of hydrostatics
    - Blood pressure
    - Intravenous bag (before drip starts)

Vernier



# Hydrodynamics

- Constant flow rate and continuity equation
- Inviscid fluids: Bernoulli’s principle
- Applications: velocity of blood flow in arteries and capillaries



## Application – Vascular Flutter

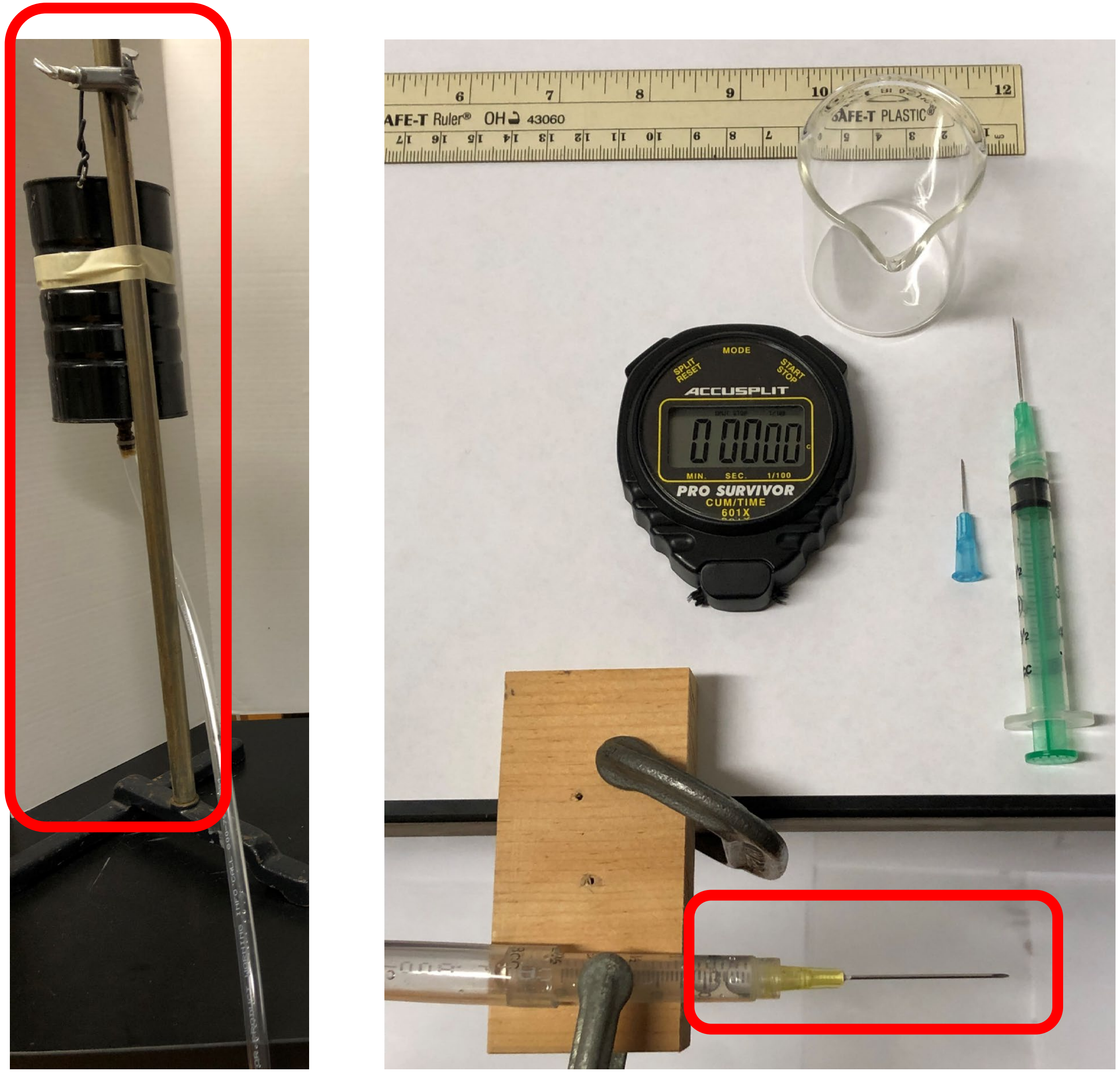
- The artery is constricted as a result of accumulated plaque on its inner walls
- To maintain a constant flow rate, the blood must travel faster than normal
- If the speed is high enough, the blood pressure is low and the artery may collapse

# Poiseuille’s law

- Viscous fluids and flow resistance

$$Q = \frac{\pi}{8\mu L} R^4 \Delta P \quad \text{where } R = radius$$

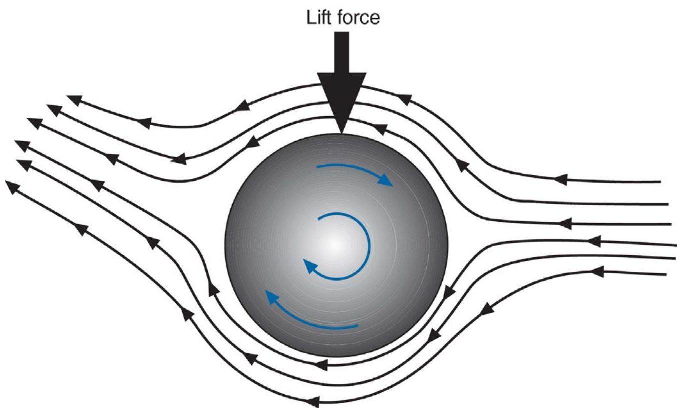
- Applications
  - Flows in needles
  - Narrowing of blood vessels and impact on blood pressure
  - Regulation of blood flow during exercise

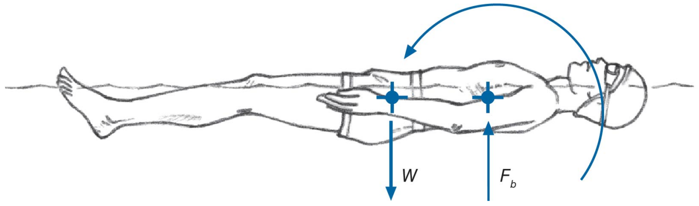


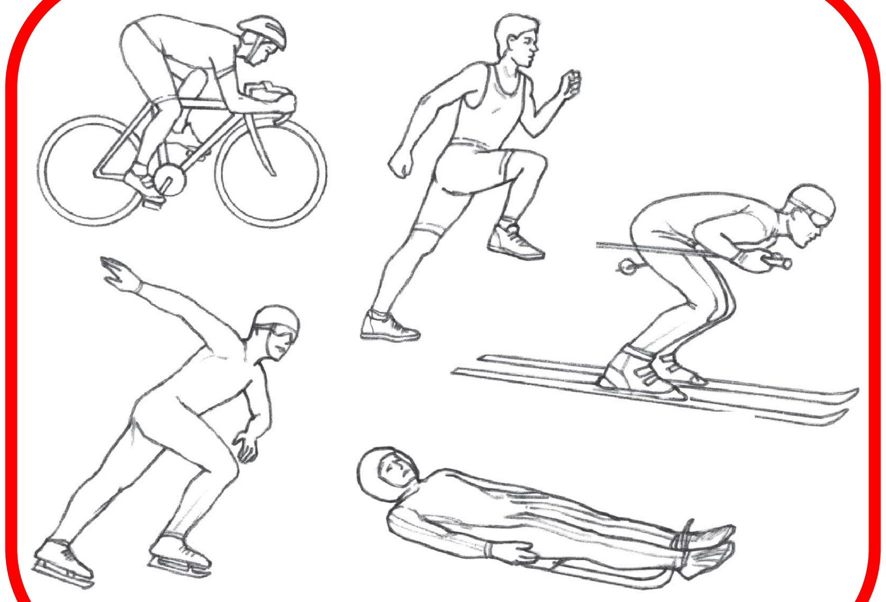
Experiment mimicking IV bag and needle in arm

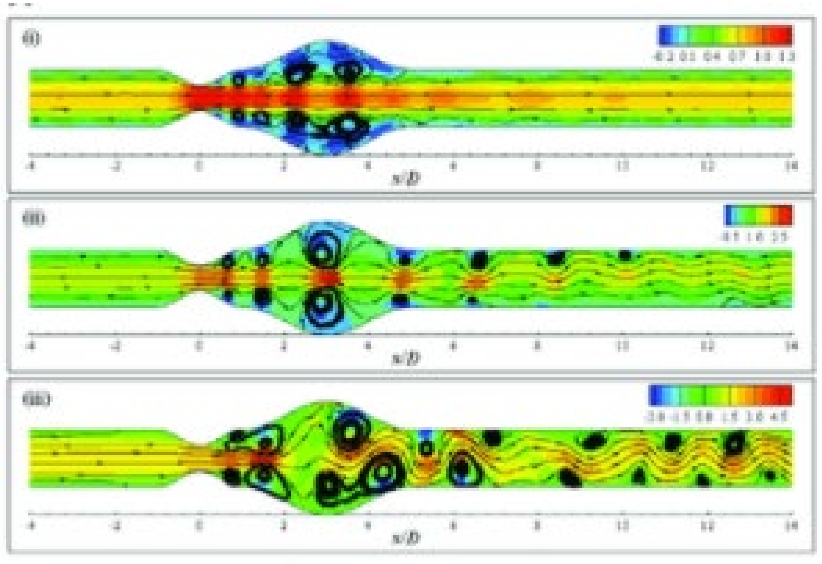
# Other hydrodynamics effects

- Buoyancy
- Drag: surface and form
- Vortex motion
- Turbulence
- Applications:
    - Swimming
    - Spinning baseball
    - Golf ball
    - Aneurysm





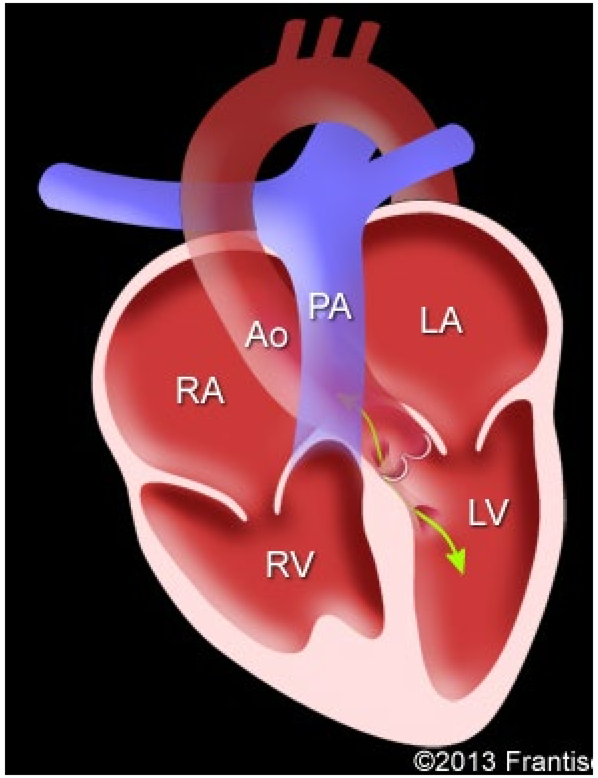




Streamlines

# Heart as a pump

- Atrium, ventricle, aorta, venous side of circulation
- Diseases of the heart



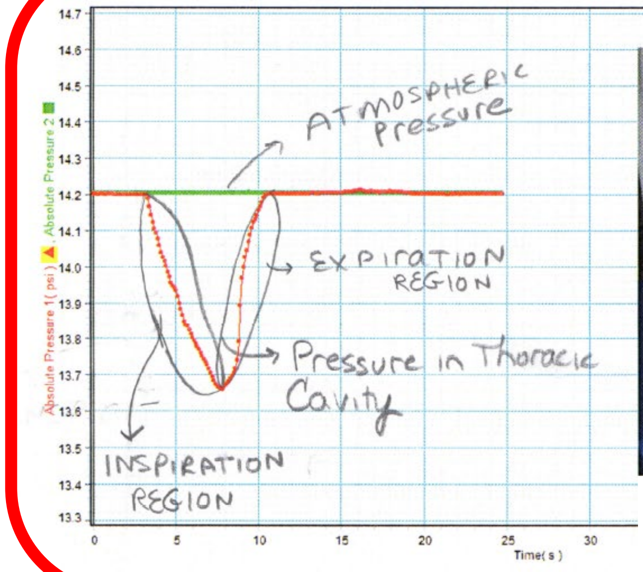

Denoyer-Geppert

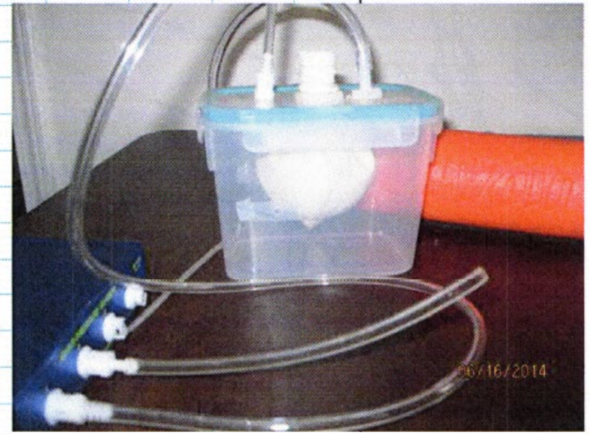
# Lungs and alveoli

- Pressure in the lung
- Laplace's law (involves surface tension)

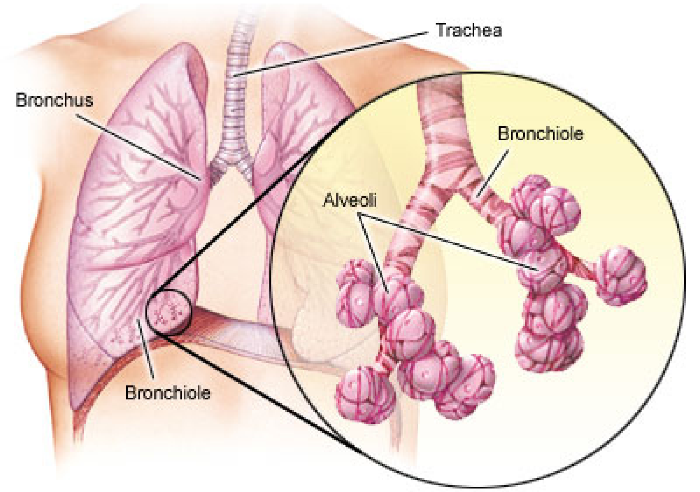
$$P = \frac{4\gamma}{r}$$

- Diseases of the lungs and alveoli
- Adapted from writeups by Donaldson





Pasco pressure sensor



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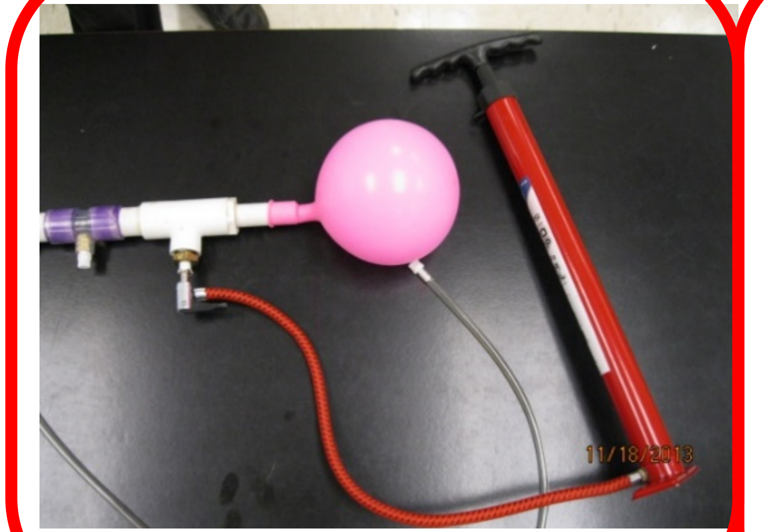
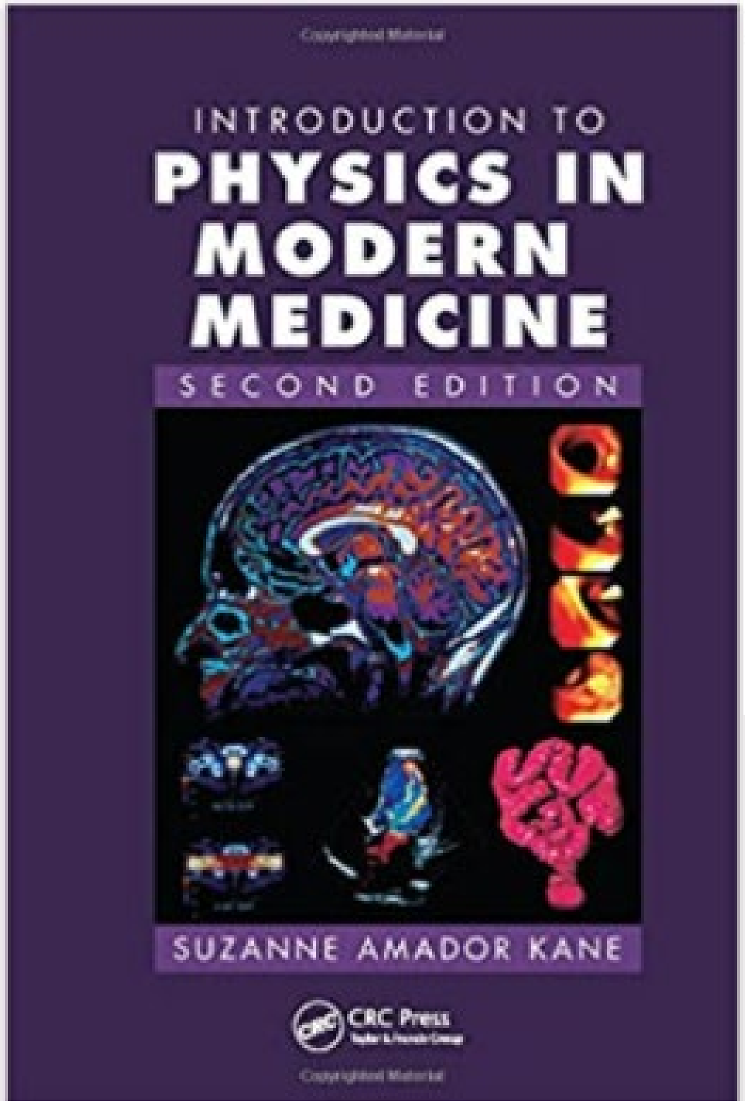


Balloon - alveolus

Punctured lung

# Diagnostic and therapeutic techniques in medicine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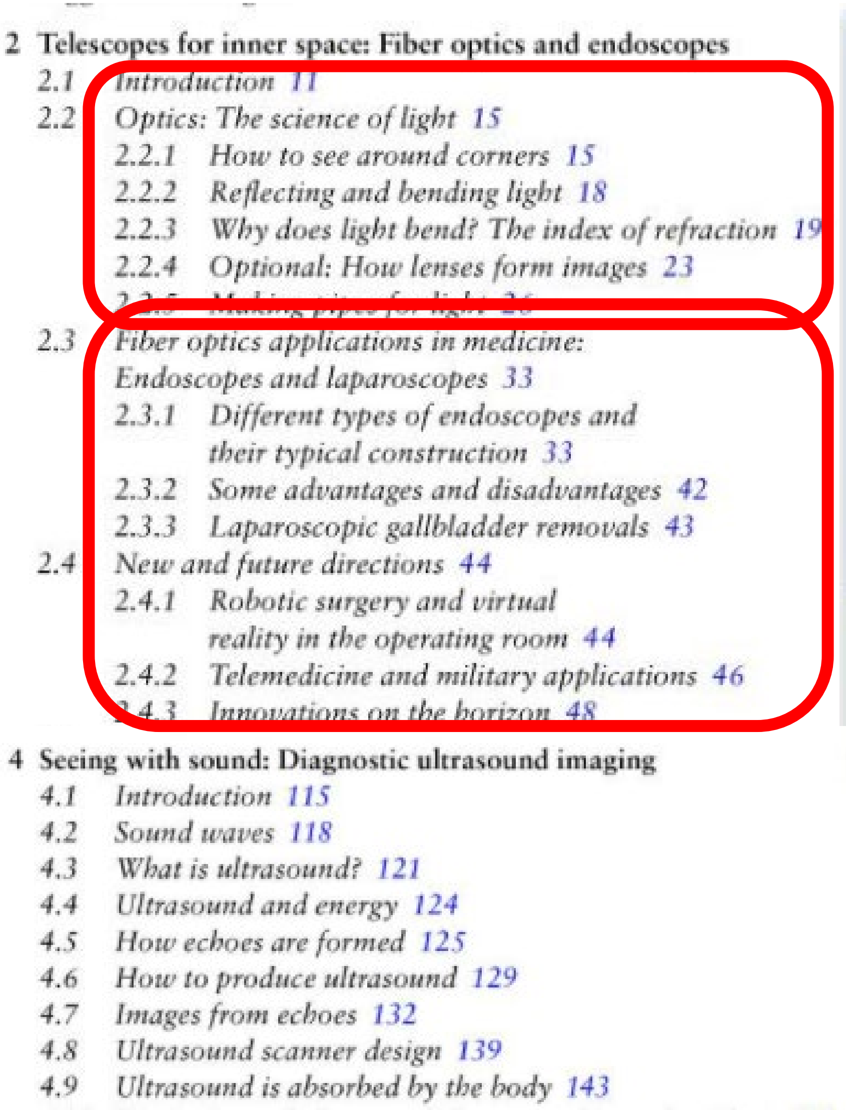

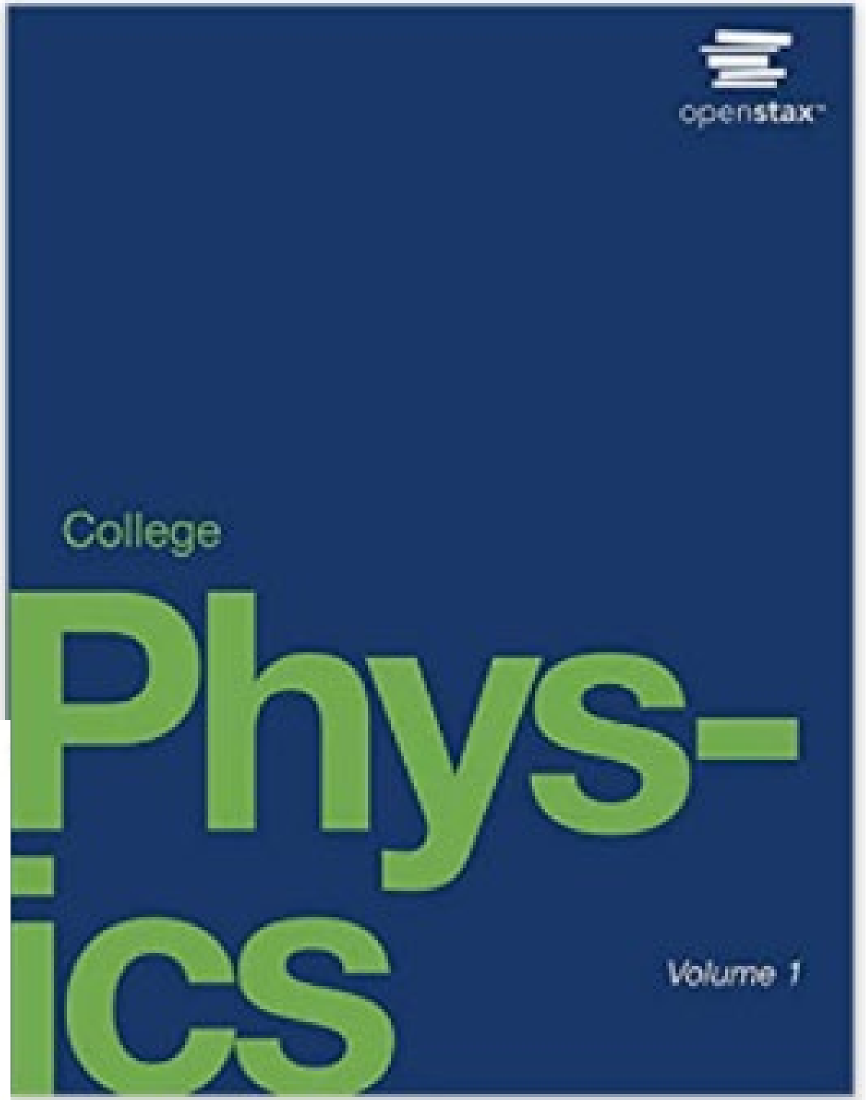
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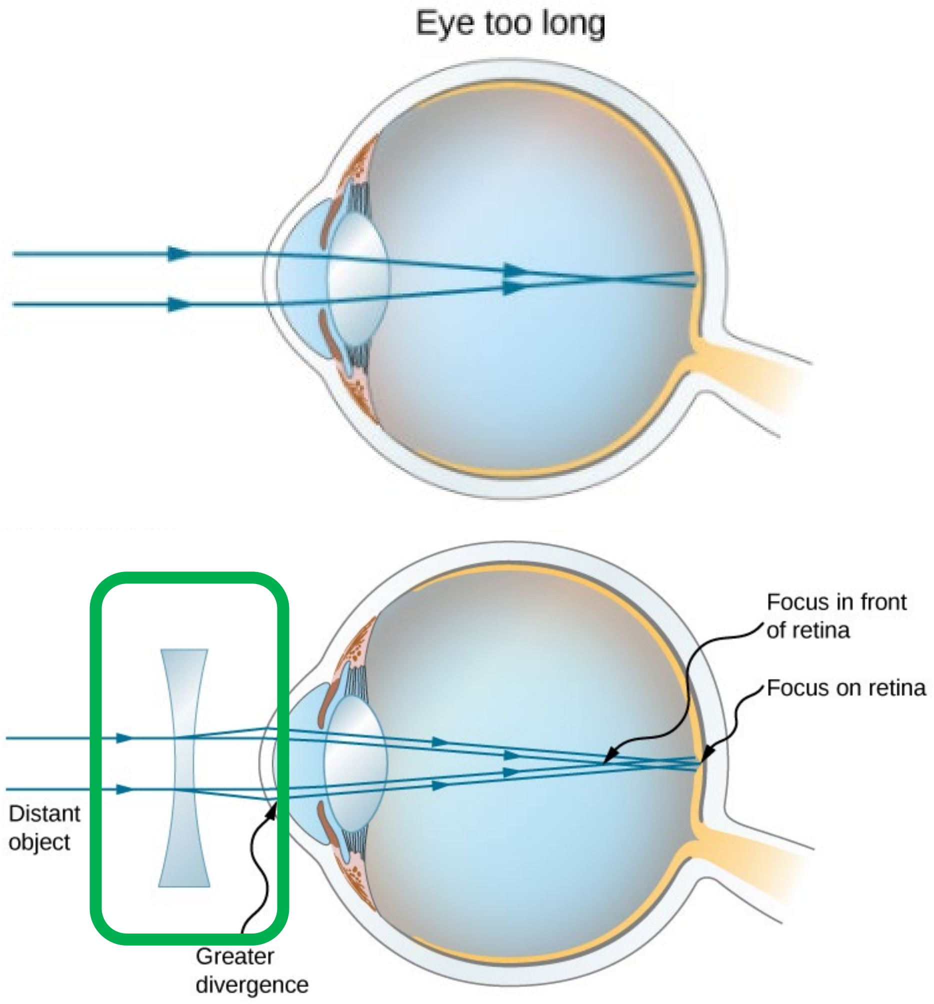
Volume 1

# Geometric optics through lens combinations

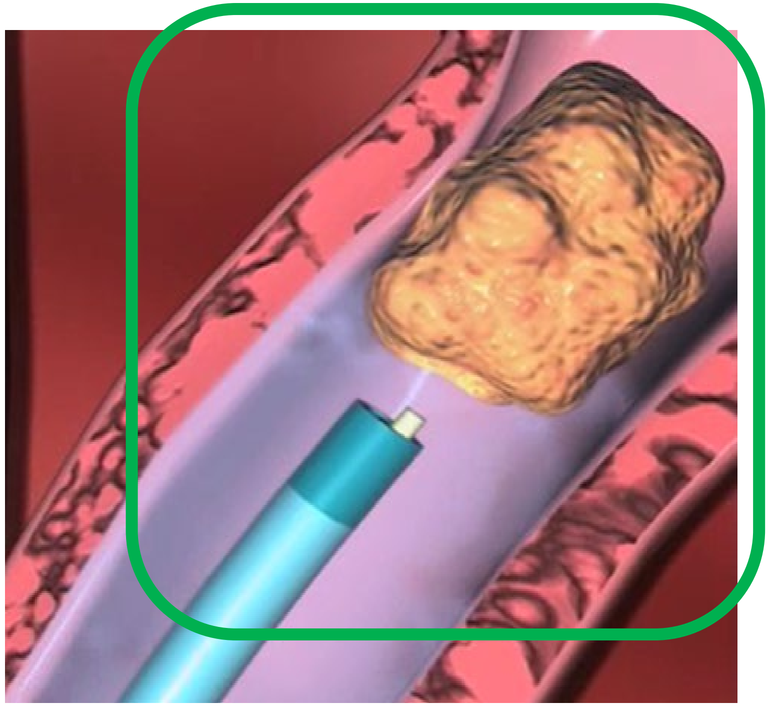
- Human eye, eyeglasses, microscope
- Eye materials adapted from Modern Miracle Medical Machines

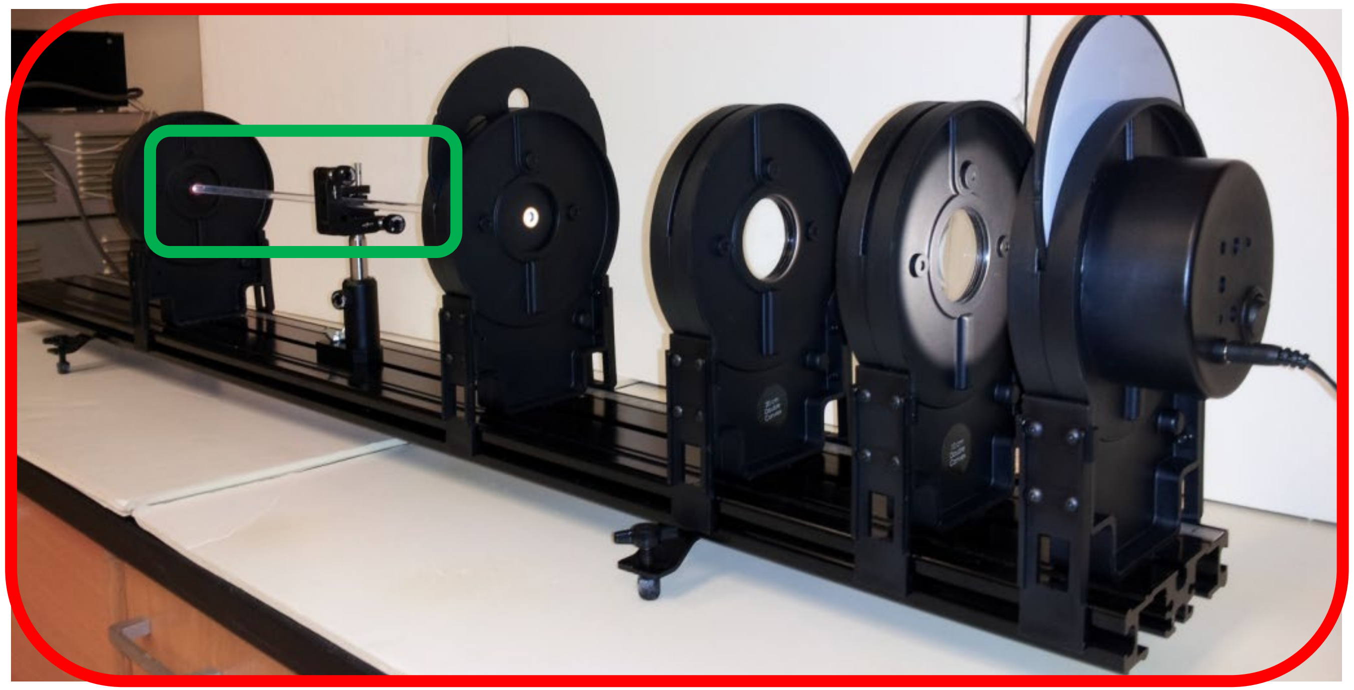


Pasco

# Fiber optics in medicine

- Basic physics: Acceptance angle and numerical aperture
- Laser coupling: needed for blasting stones
- Illumination and imaging in endoscopy
- Intermediate level developed by Lowe, Spiro and Donaldson



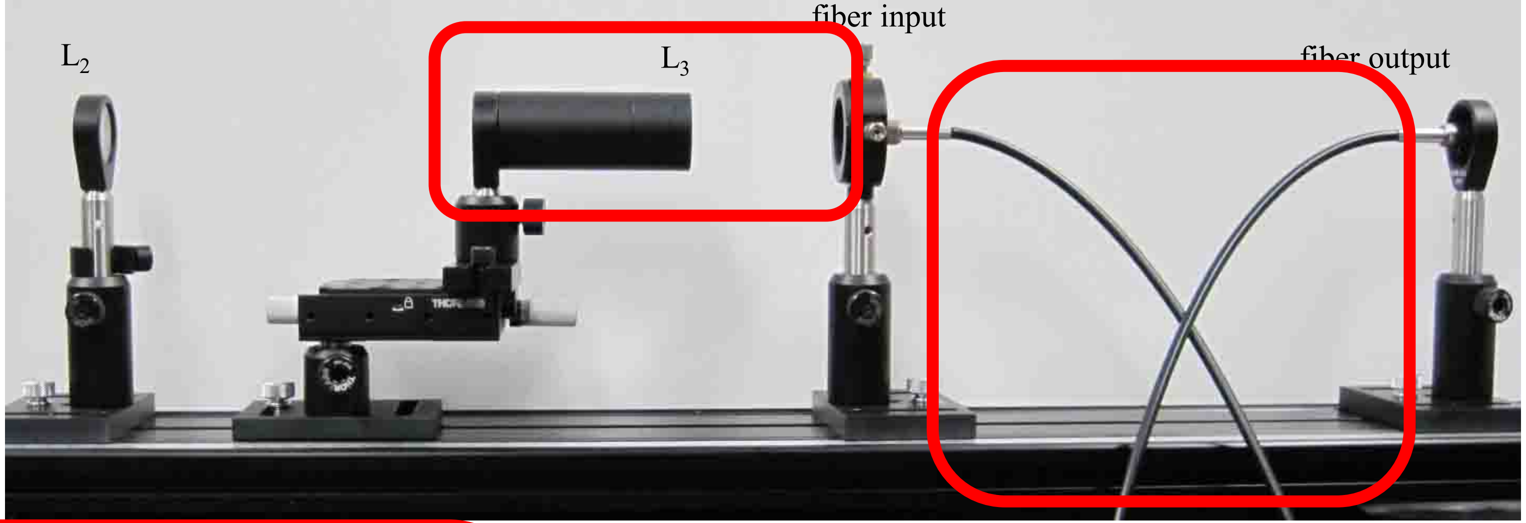


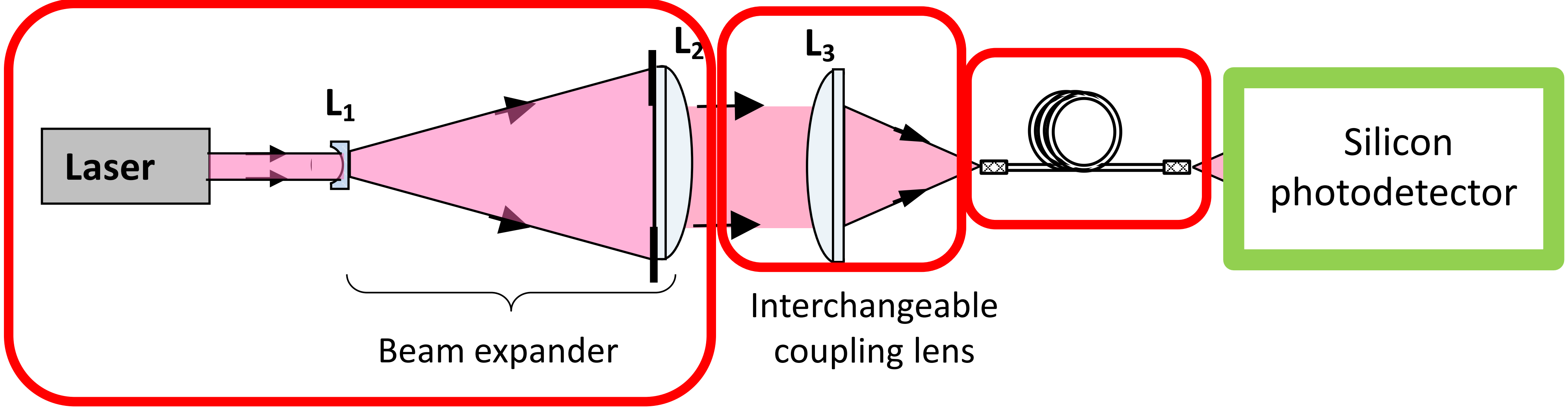
Vernier

# Advanced apparatus on fiber optics

- Acceptance angle and coupling
- Developed with Spiro

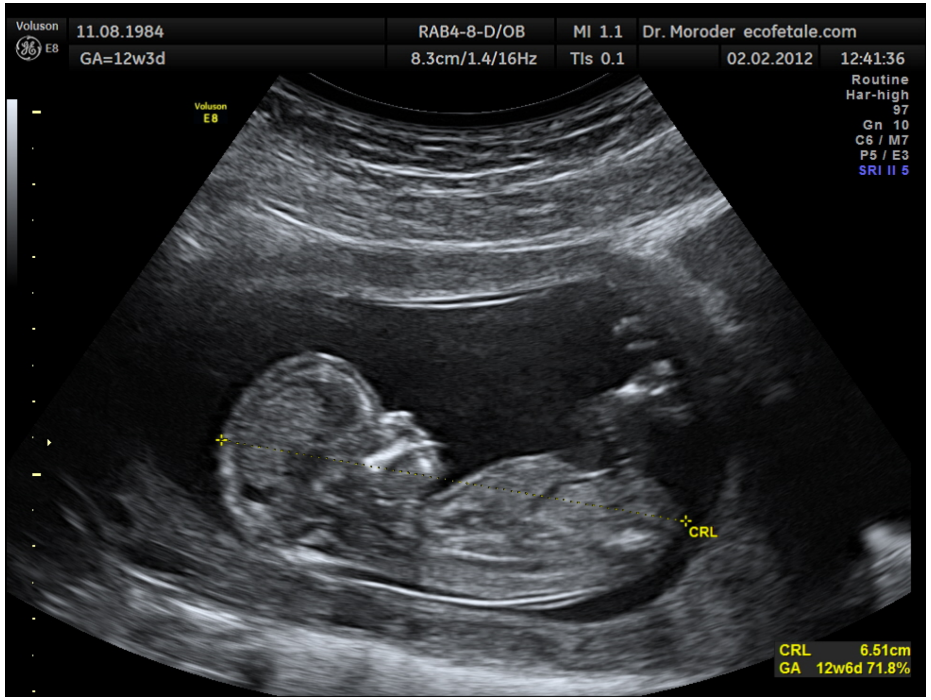
Mostly Thorlabs
Fiber–various sources

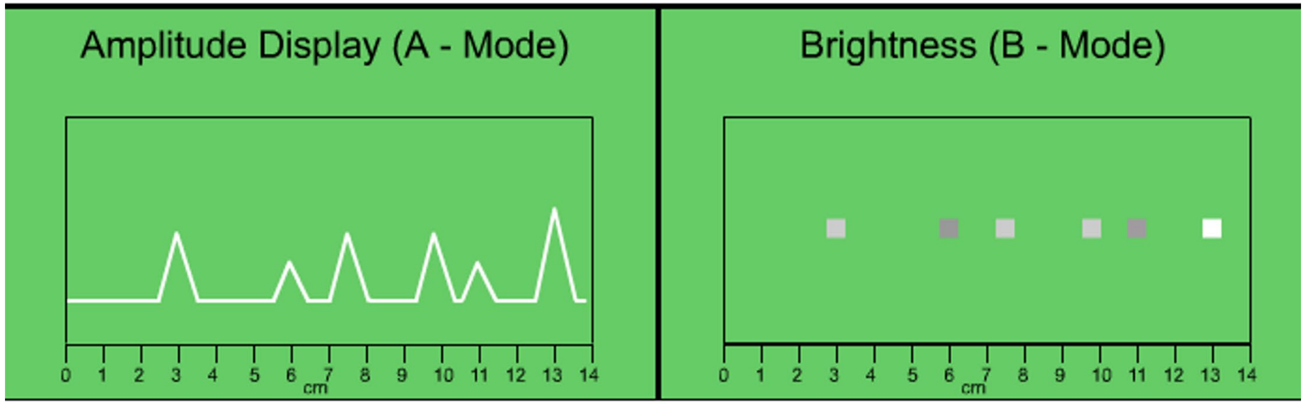




# Ultrasound imaging

- Basic physics of reflection, transmission, absorption, diffraction
- Paper-and-pencil exercises
  - Calculate echo times.
  - A scan and B scan → 2D image





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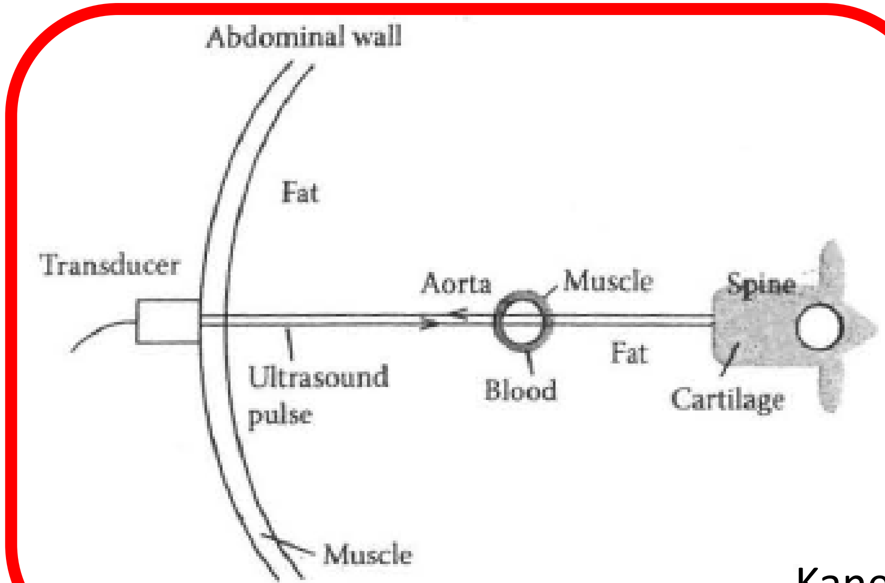
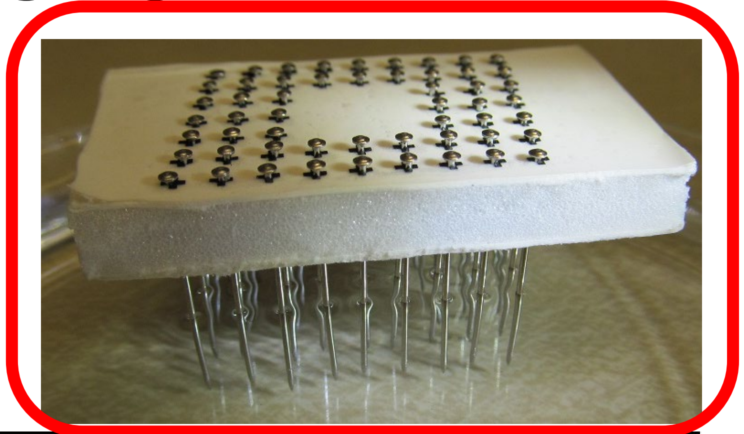
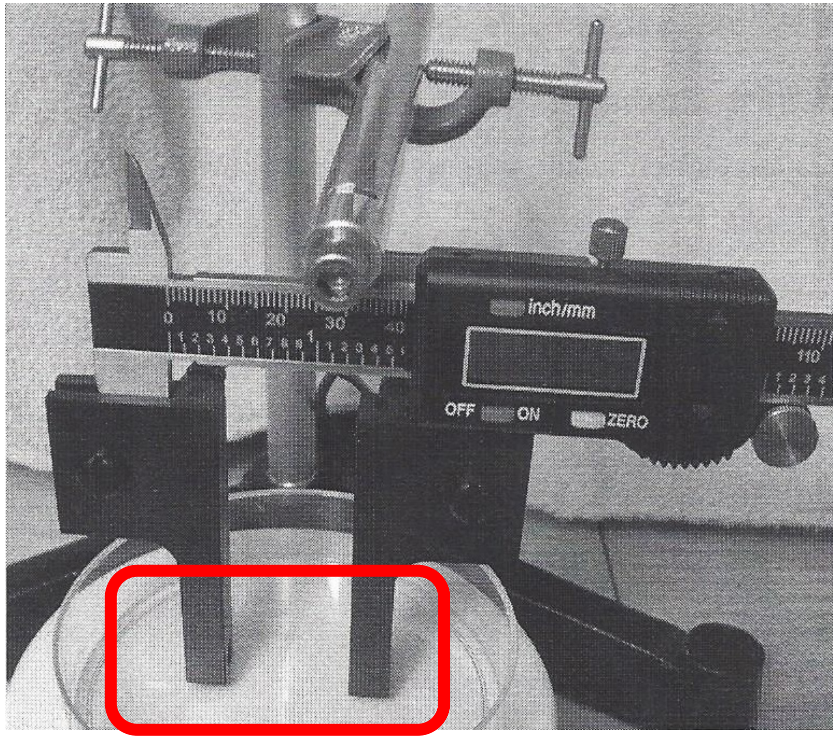


Kane

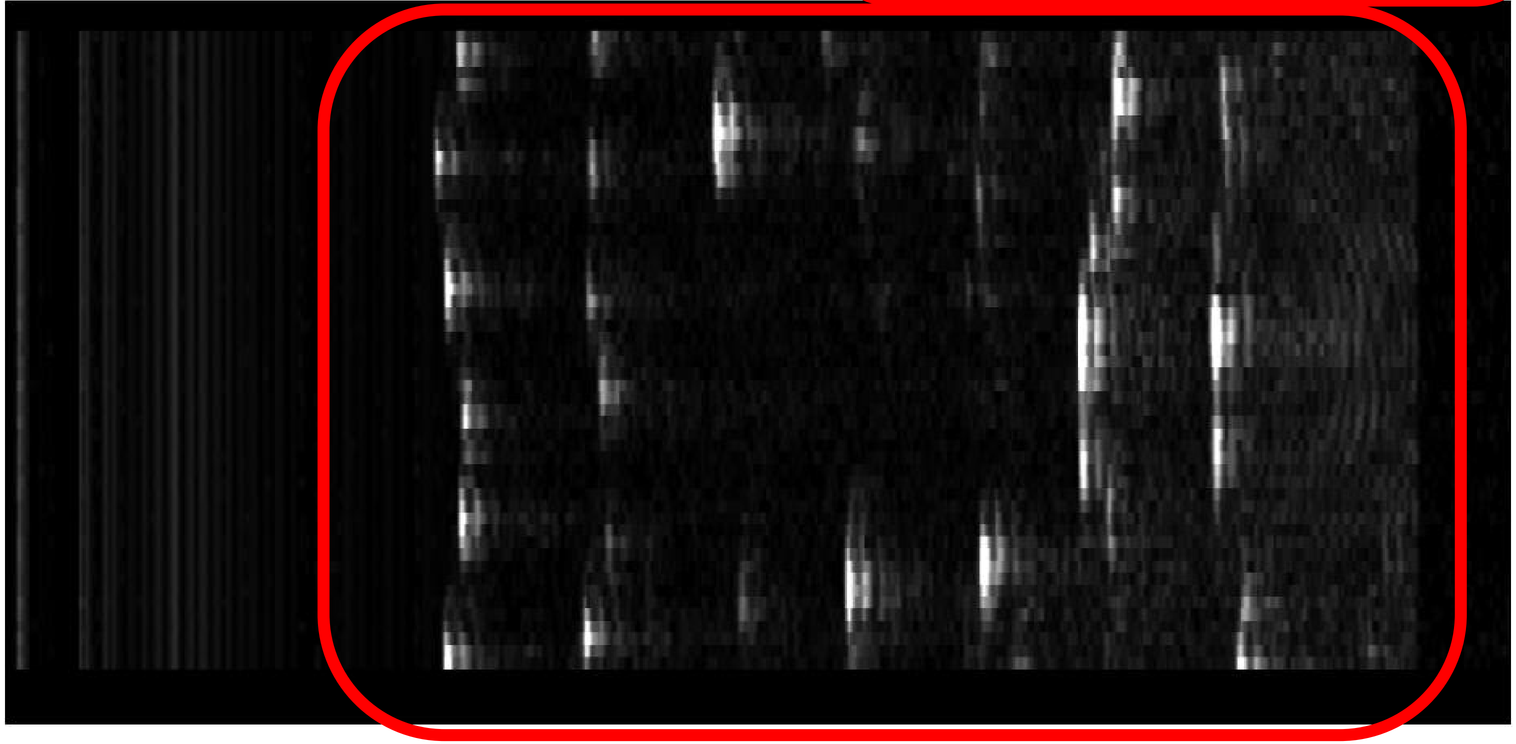
# Advanced apparatus on ultrasound imaging

- Basic ultrasound physics
- Electronic instrumentation, Matlab
- Array of steel pins --> measure signal and construct image





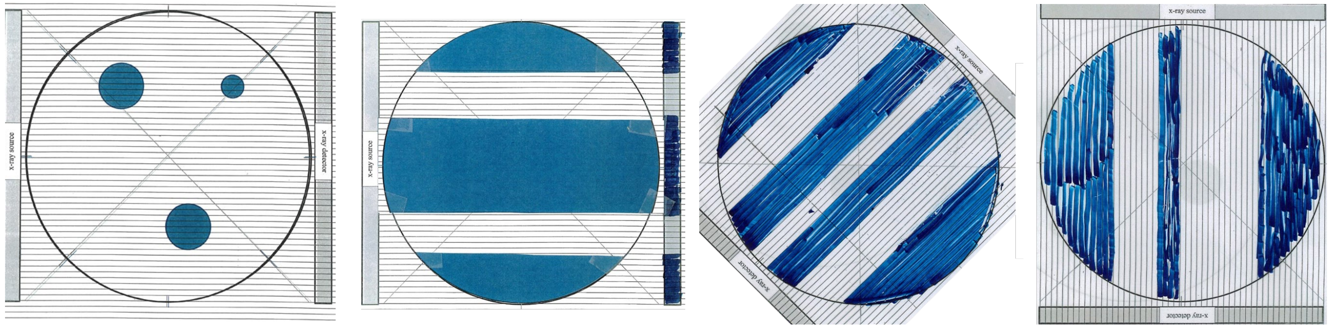
Iowa Doppler Products

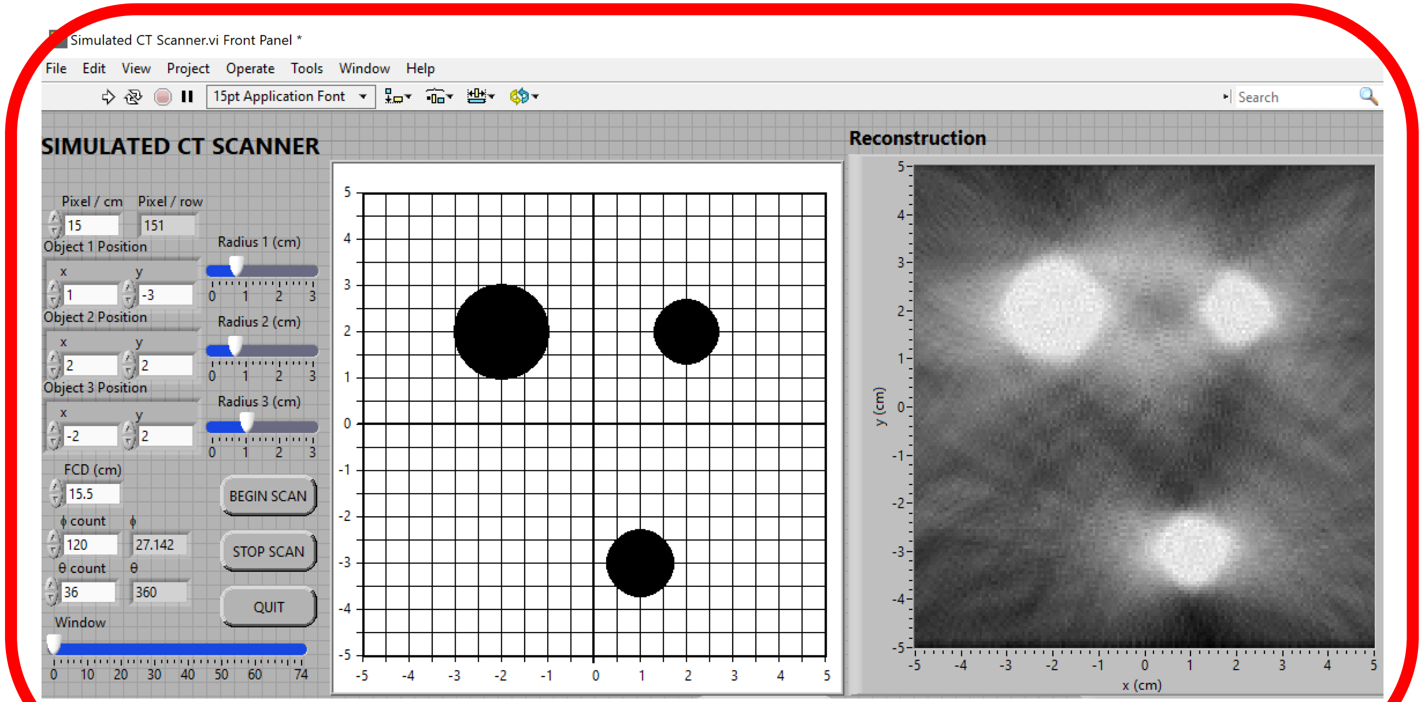


Adapted from suggestions by Ron Vogel

# Computed tomography (CT)

- Basic physics of X-rays
- Medical applications
- CT: how to create 2D image
  - Back projection
  - LabView simulation (Mylott et al)





Pixel / cm 15
Pixel / row 151
Object 1 Position x 1 y -3
Radius 1 (cm)
Object 2 Position x 2 y 2
Radius 2 (cm)
Object 3 Position x -2 y 2
Radius 3 (cm)
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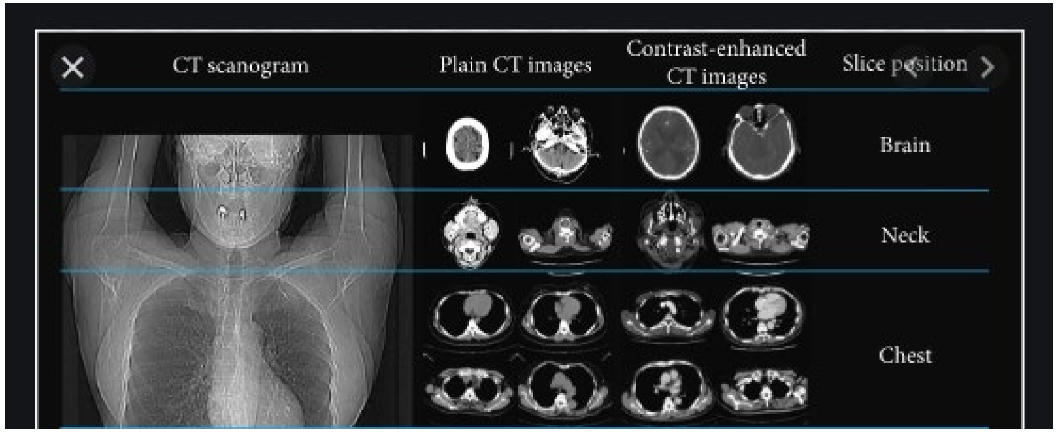
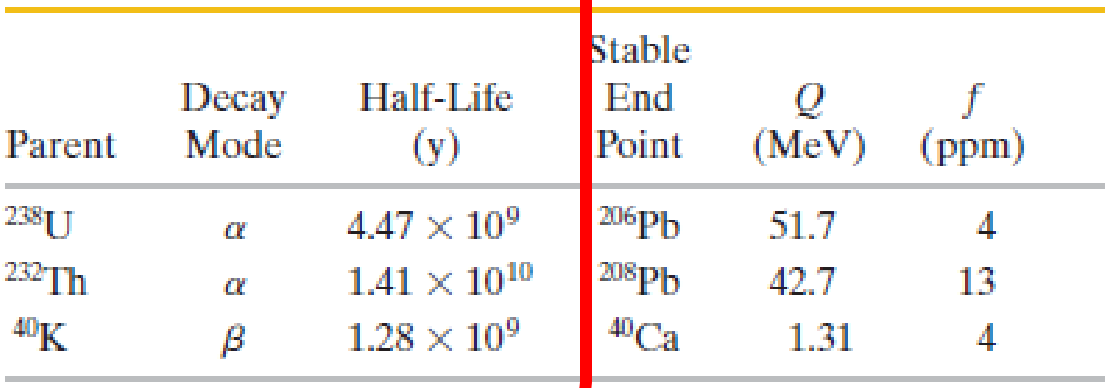
θ count 36
θ 360
Window



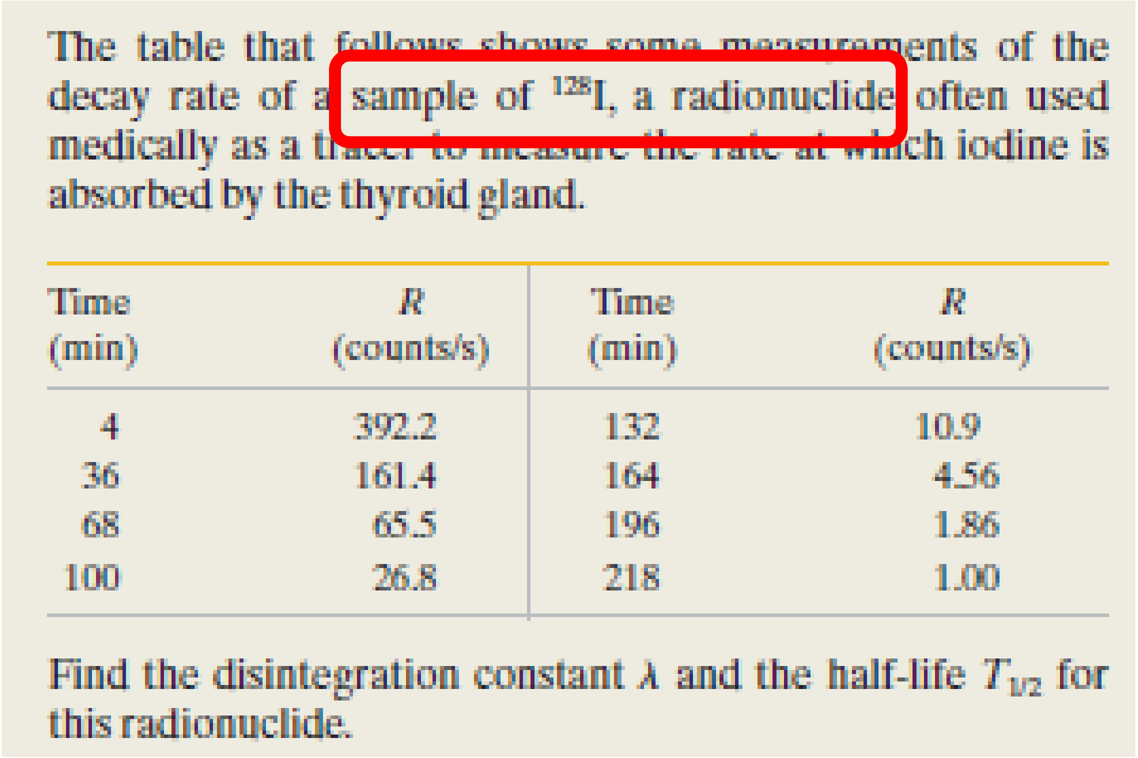
# Nuclear physics

- I prefer to use the nuclear physics chapter from a standard intro textbook
- Radioactive decay → radiopharmaceuticals
- PET and gamma camera imaging

Table from standard text.



| Parent | Decay Mode | Half-Life (y) | Stable End Point | $Q$ (MeV) | $f$ (ppm) |
|---|---|---|---|---|---|
| $^{238}$U | $\alpha$ | $4.47 \times 10^9$ | $^{206}$Pb | 51.7 | 4 |
| $^{232}$Th | $\alpha$ | $1.41 \times 10^{10}$ | $^{208}$Pb | 42.7 | 13 |
| $^{40}$K | $\beta$ | $1.28 \times 10^9$ | $^{40}$Ca | 1.31 | 4 |



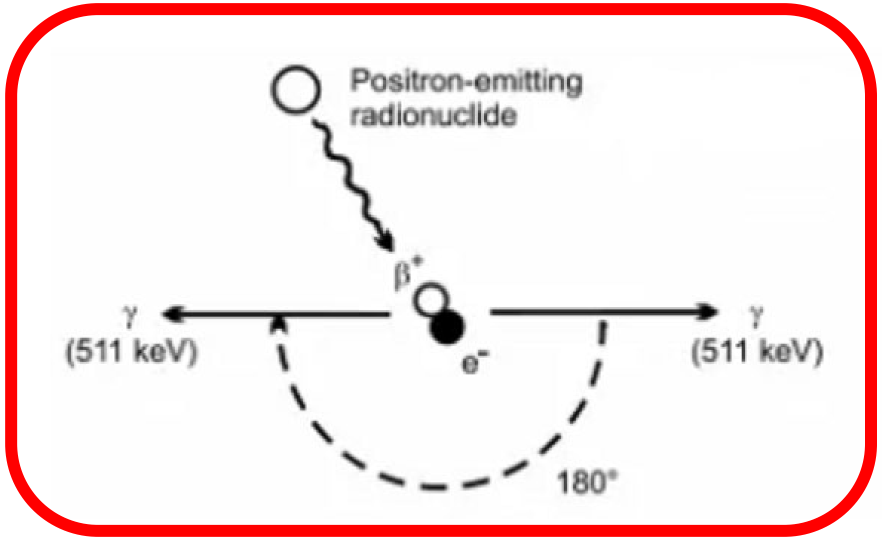
The table that follows shows some measurements of the decay rate of a sample of $^{128}$I, a radionuclide often used medically as a tracer to measure the rate at which iodine is absorbed by the thyroid gland.

| Time (min) | $R$ (counts/s) | Time (min) | $R$ (counts/s) |
|---|---|---|---|
| 4 | 392.2 | 132 | 10.9 |
| 36 | 161.4 | 164 | 4.56 |
| 68 | 65.5 | 196 | 1.86 |
| 100 | 26.8 | 218 | 1.00 |

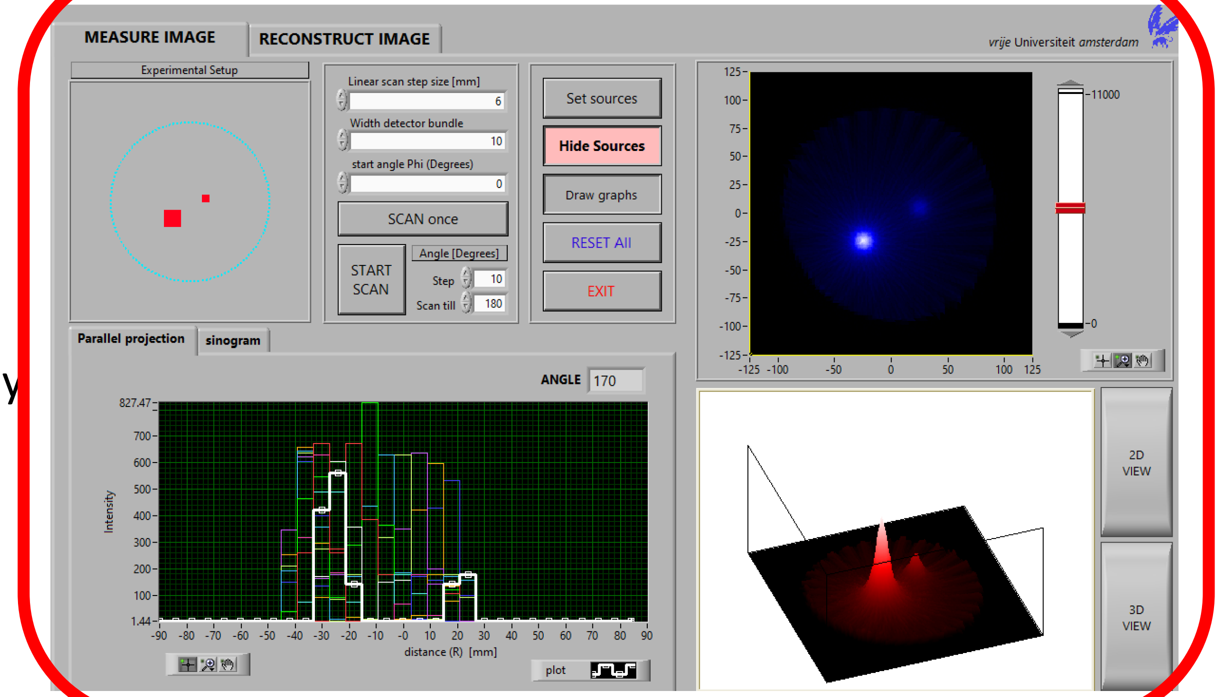
Find the disintegration constant $\lambda$ and the half-life $T_{1/2}$ for this radionuclide.

# Positron emission tomography (PET)

- Gamma ray coincidence measurements
- Track and carts for time-of-flight concepts
- PET software shows principles and <u>filtered</u> back projection
- Instructional materials adapted from Modern Miracle Medical Machines



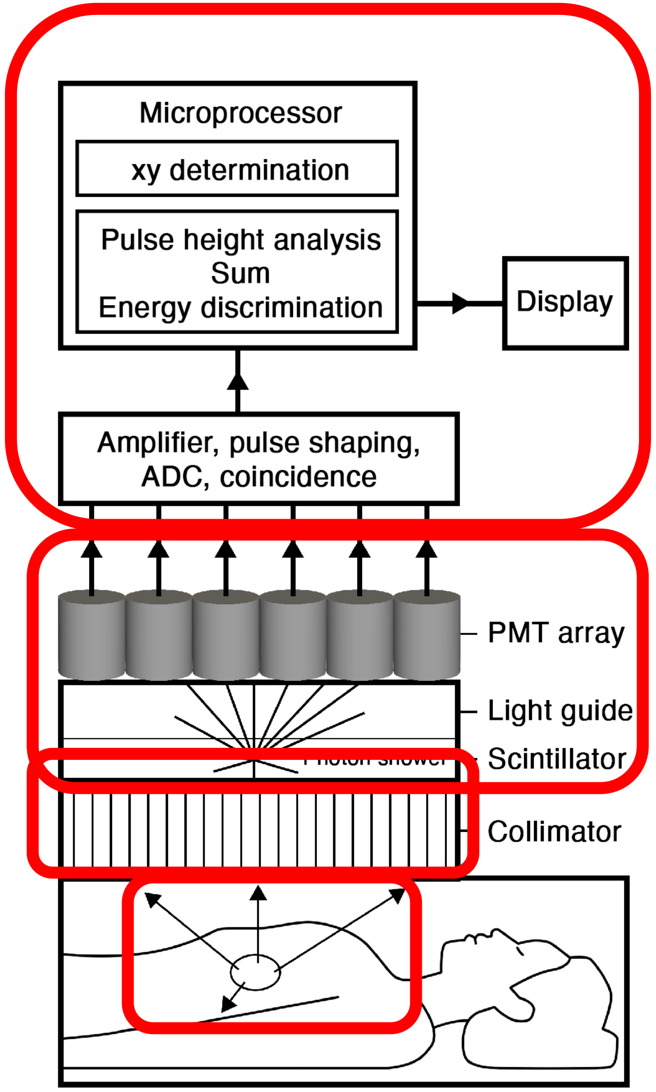
LabView VI by Jan Mulder



Linear scan step size [mm] 6
Width detector bundle 10
start angle Phi (Degrees) 0
Angle [Degrees] Step 10 Scan till 180
ANGLE 170

# Gamma camera imaging → SPECT

- Radiopharmaceutical is concentrated in an organ.
- Image is composed of dots. Each dot represents the position of a gamma ray photon emitted from human body.
- Collimator
- Detection system
- Electronics and microprocessor
- Instructional materials developed by Lowe and Spiro



Microprocessor

xy determination

Pulse height analysis
Sum
Energy discrimination

Display

Amplifier, pulse shaping,
ADC, coincidence

PMT array

Light guide

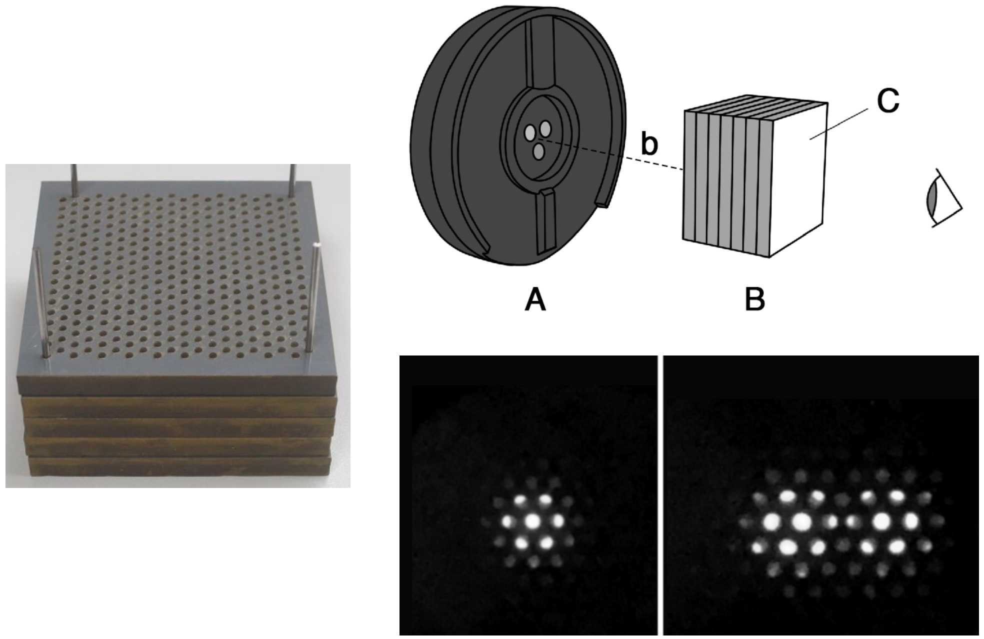
Photon shower

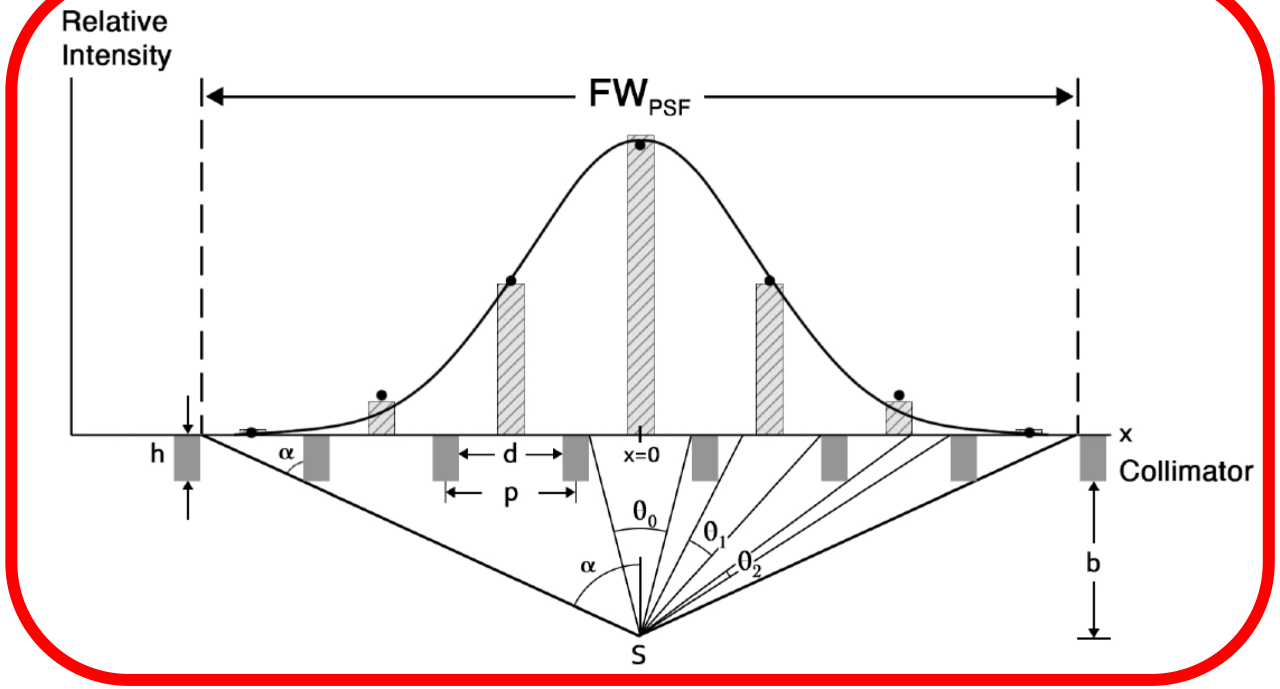
Scintillator

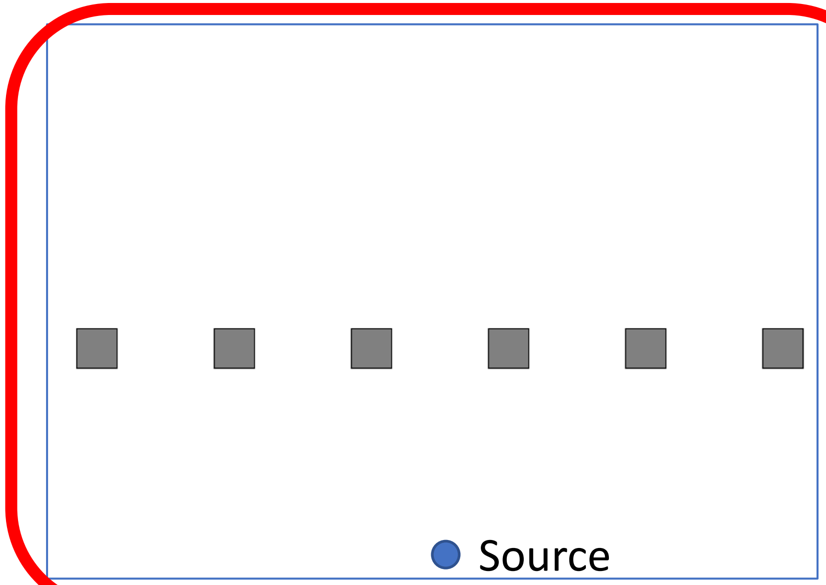
Collimator

# Gamma camera: collimator

- Ray tracing
- Experiment with LEDs → image resolution
- More advanced
  - Write ray tracing software (Behringer)
  - Measure light intensity distributions and compare with theoretical predictions

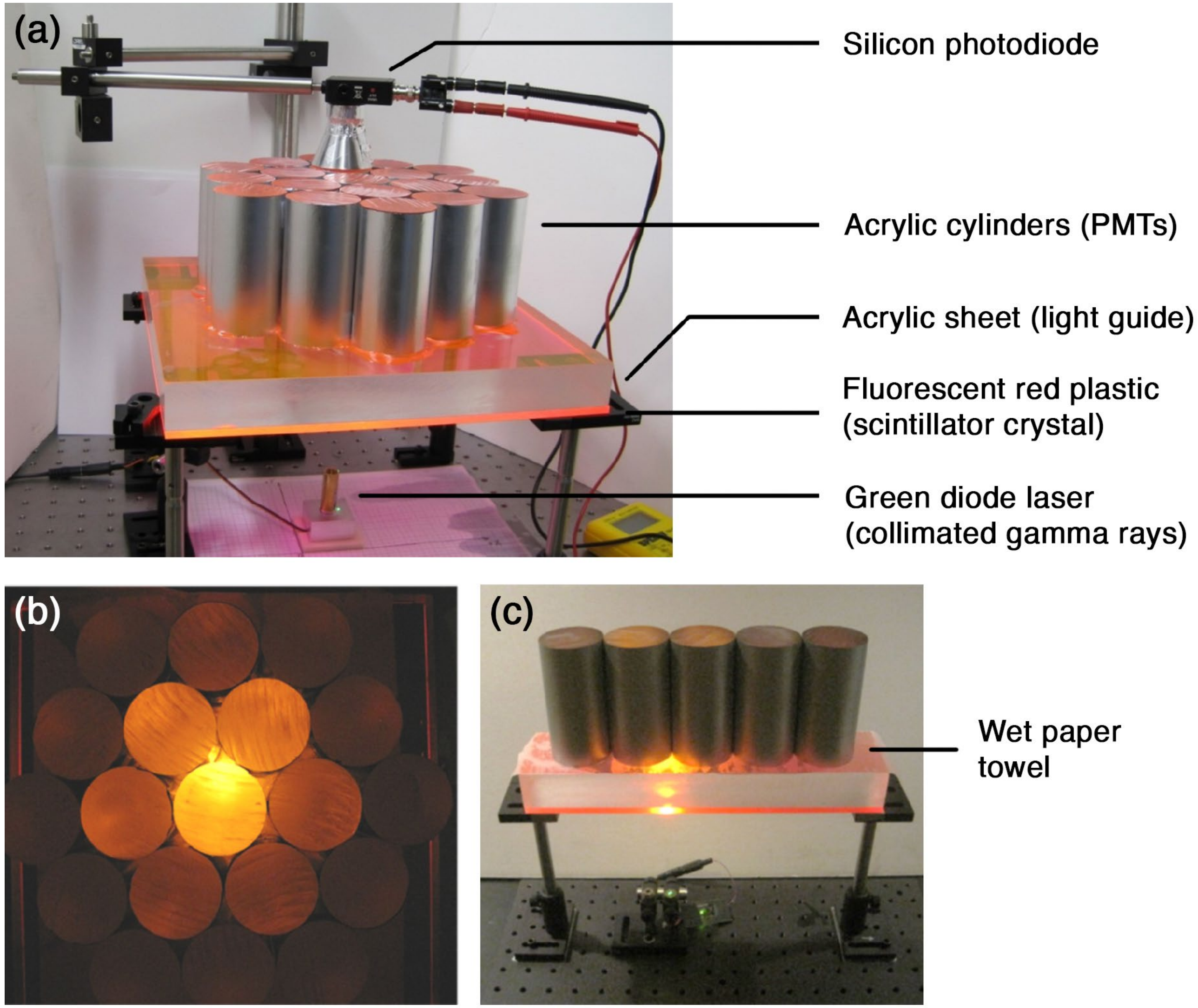






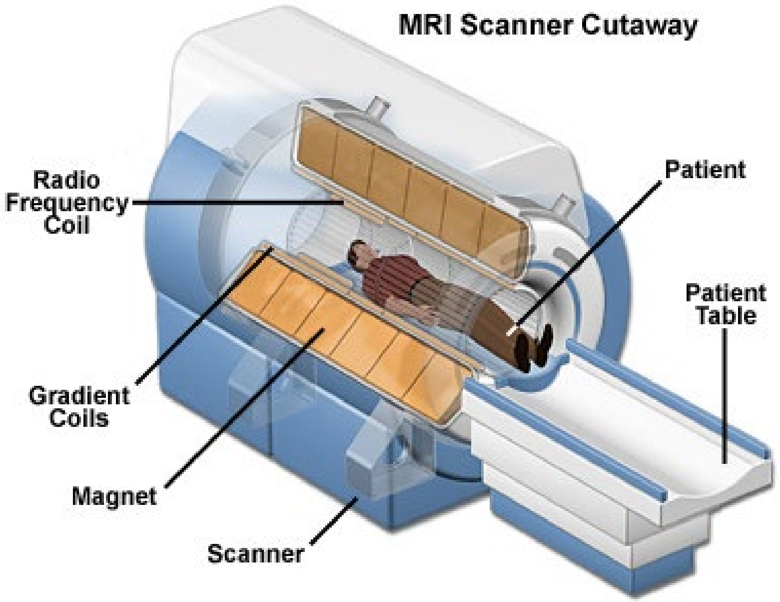
# Gamma camera: detection system

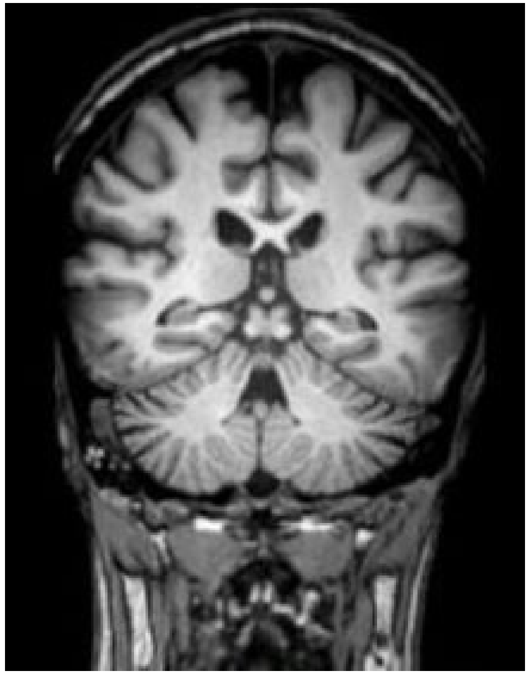
- Gamma ray photon is detected with a scintillator crystal
- Array of PMTs enables 2D image to be constructed.
- Excel
- Hospitals have SPECT systems, capable of 3D imaging.

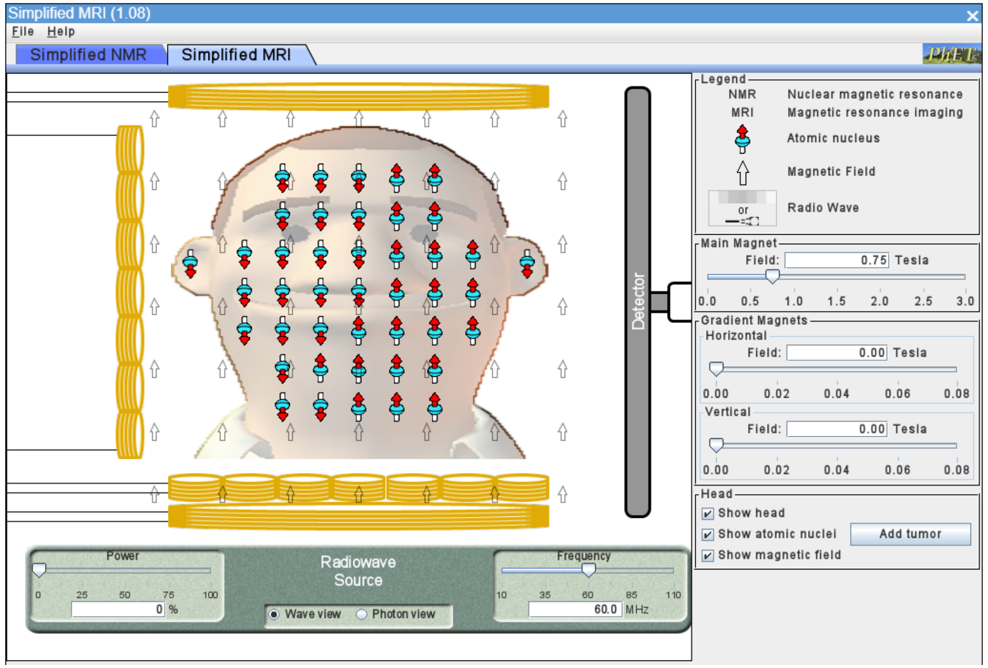


# Magnetic resonance imaging (MRI)

- Based on nuclear magnetic resonance.
- PHET software. Good for understanding purpose of magnetic field gradient coils.
- Instructional materials need to be developed on how an image is formed from rf signal.







Legend

NMR Nuclear magnetic resonance

MRI Magnetic resonance imaging

Atomic nucleus

⇧ Magnetic Field

or Radio Wave

Main Magnet

Field: 0.75 Tesla

Gradient Magnets

Horizontal

Field: 0.00 Tesla

Vertical

Field: 0.00 Tesla

Head

☑ Show head

☑ Show atomic nuclei

☑ Show magnetic field

Power: 0 %

● Wave view ○ Photon view

Frequency: 60.0 MHz

# Summary

- Physics of medicine courses at Loyola
  - Topics in biomechanics and fluid mechanics
  - Diagnostic and therapeutic techniques in medicine
- In this talk, I have focused on activities in our courses. Lecture, traditional homework problems and reading are also essential for learning.
- Suitable for STEM majors
- Intro to advanced levels of physics

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Presentation on Jan 7 at 3:30 pm. Session A3.
Biophysics in the 21st Century Curriculum I, moderator: Mariel Meier/Bob Hilborn
Abstract ID 3821

Administered by the physics department, a biomedical physics minor was implemented at Loyola University Maryland. Two courses were developed: one on sport and biomechanics, and the other on therapeutic and diagnostic techniques in medicine. While most of the materials are at the intermediate-level, appropriate for students majoring in various STEM disciplines, the materials can be adapted for introductory and advanced levels. Lectures, reading, and problem sets are enriched with experimentation, demonstrations, paper-and-pencil, and computer activities. This talk will survey many of the course topics and how we have introduced modeling in the courses. Examples include fiber optics in medicine, computed tomography, positron emission tomography, and gamma camera imaging. For biomechanics, examples will be drawn from a dissection, metabolic efficiency, biomechanics of the arm, leg, and back, analysis of simple motions in sports, and the heart as a pump.