Introduction to Bioengineering and Biomedical Devices

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Course Objective

- To introduce the fundamental concepts that are required for the design and applications of biomedical prosthetics
- Understand the basic concepts of material, biology and mechanics with relation to prosthetics
- Understand relevant issues such as biocompatibility, trauma, bone loss, wear

Course Outline

- Introduction to biological materials and biomedical devices
- Cell/surface interactions
- Tissue engineering
- Wear of biomaterials
- Nanoparticles and BioMEMS for cancer detection and treatment

Introduction to Biomaterials Sci. & Eng.

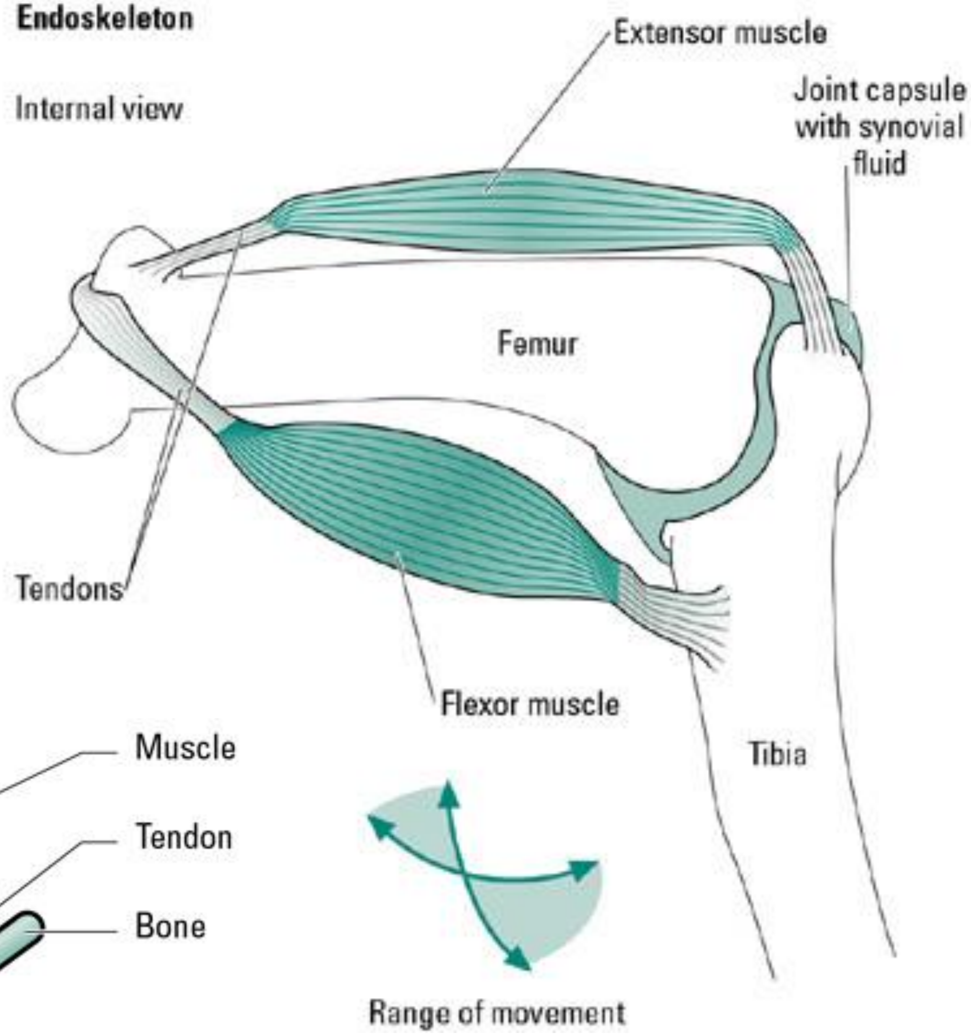
- Material Concern:
  - Chemical bonding,
  - Structure & surface characterization
  - Bulk properties
- Types of material used in medicine
  - Metals
  - Polymers
  - Ceramics
  - Composites

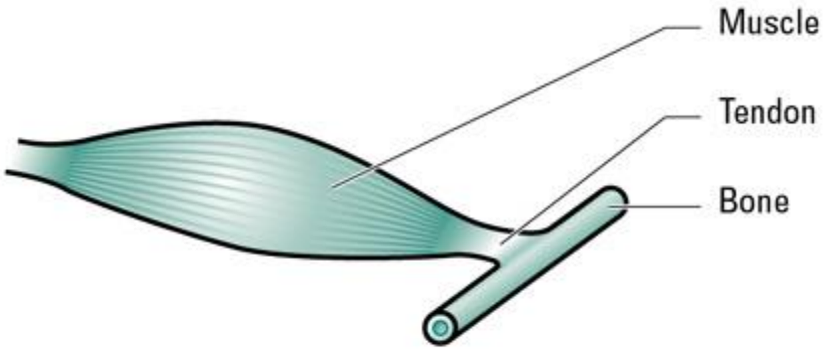
Review of Biology and Biomedical Devices

- Musculoskeletal structure
- Biomedical devices
- Proteins structure, properties, and adhesion to surfaces
- Cell/Tissue properties and interactions with their environment
- Host reaction to biomaterials

The Human Musculoskeletal System

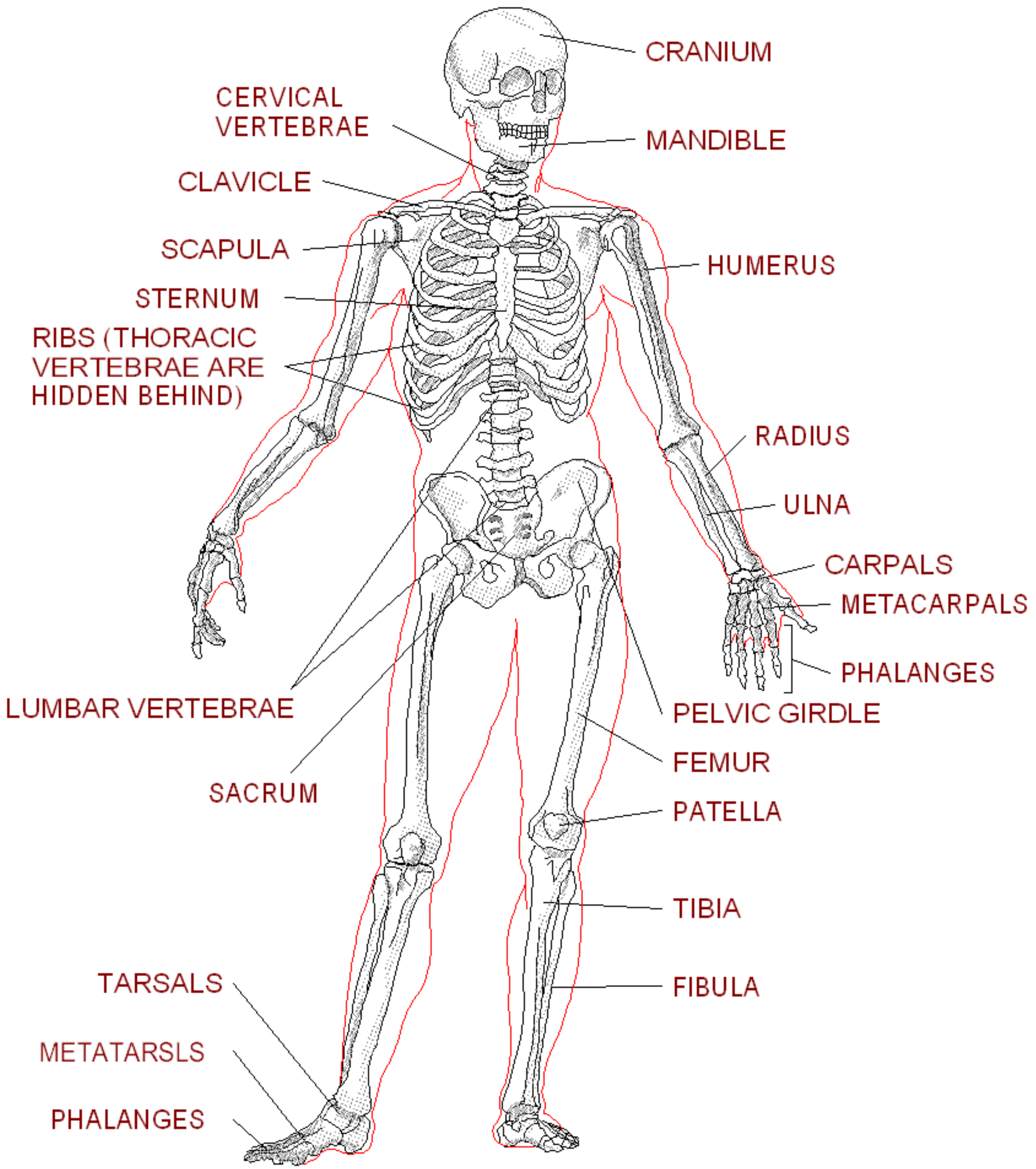
- Endoskeleton consists of hard supporting elements such as bones buried within soft tissues





The Human Musculoskeletal System

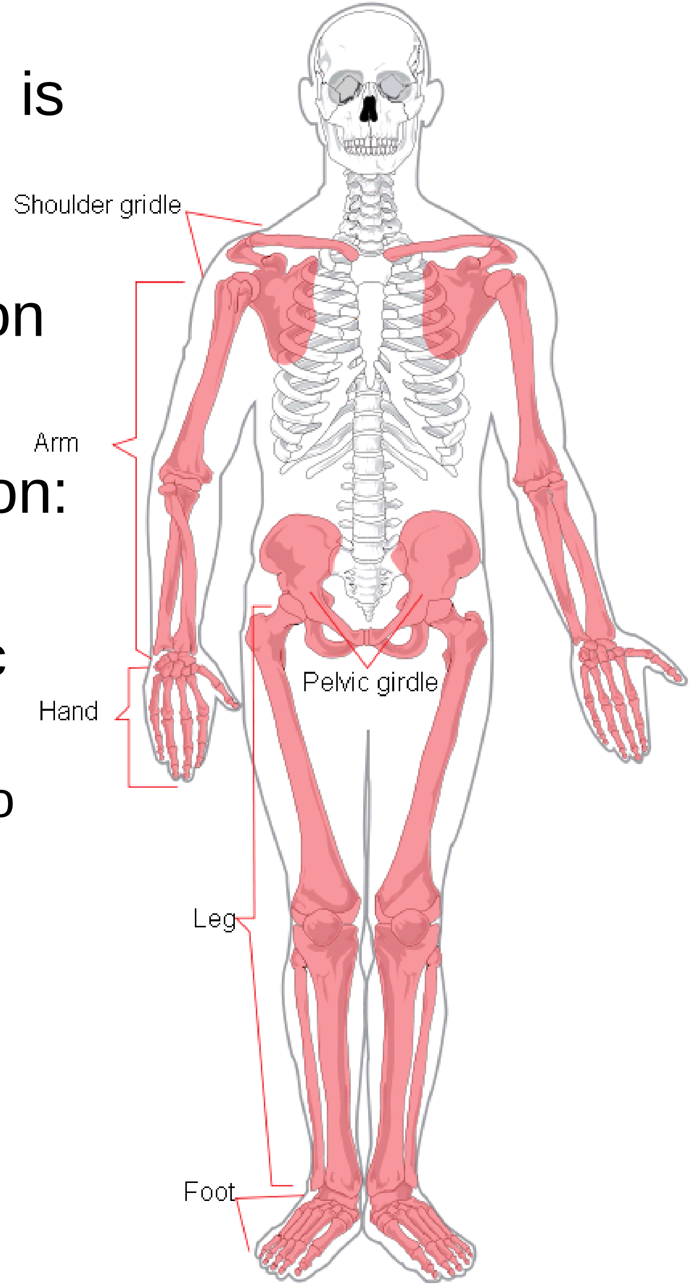
- The human body is build from 206 bones:
  - Some are fused together
  - Other are connected by ligaments that allow freedom of Rotation

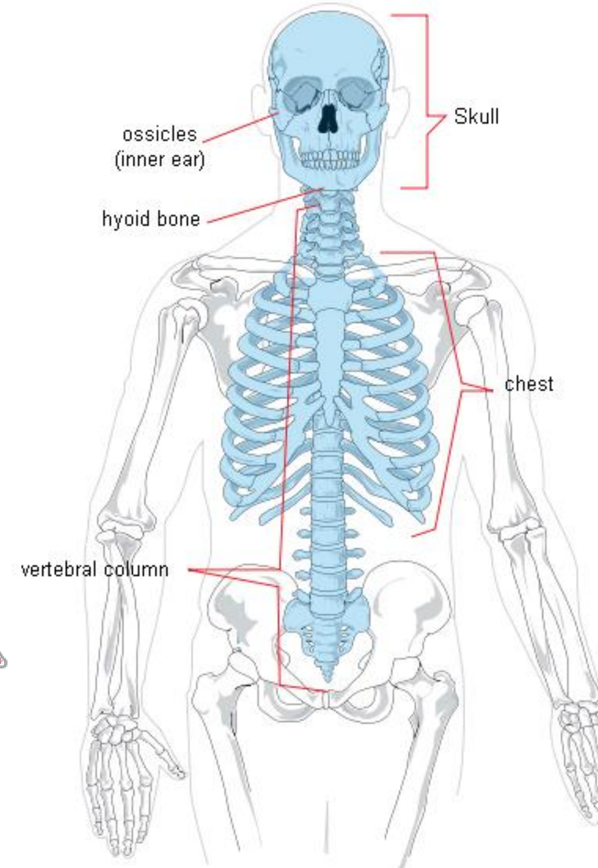


From: http://cas.bellarmine.edu

The Human Musculoskeletal System

- The human skeleton is divided into the axial skeleton and the appendicular skeleton
- Appendicular skeleton:
  - Limb bones
  - Pectoral and pelvic girdles
    - Point of anchor to axial skeleton
- Axial skeleton
  - Skull
  - Vertebral Column
  - Rib cage





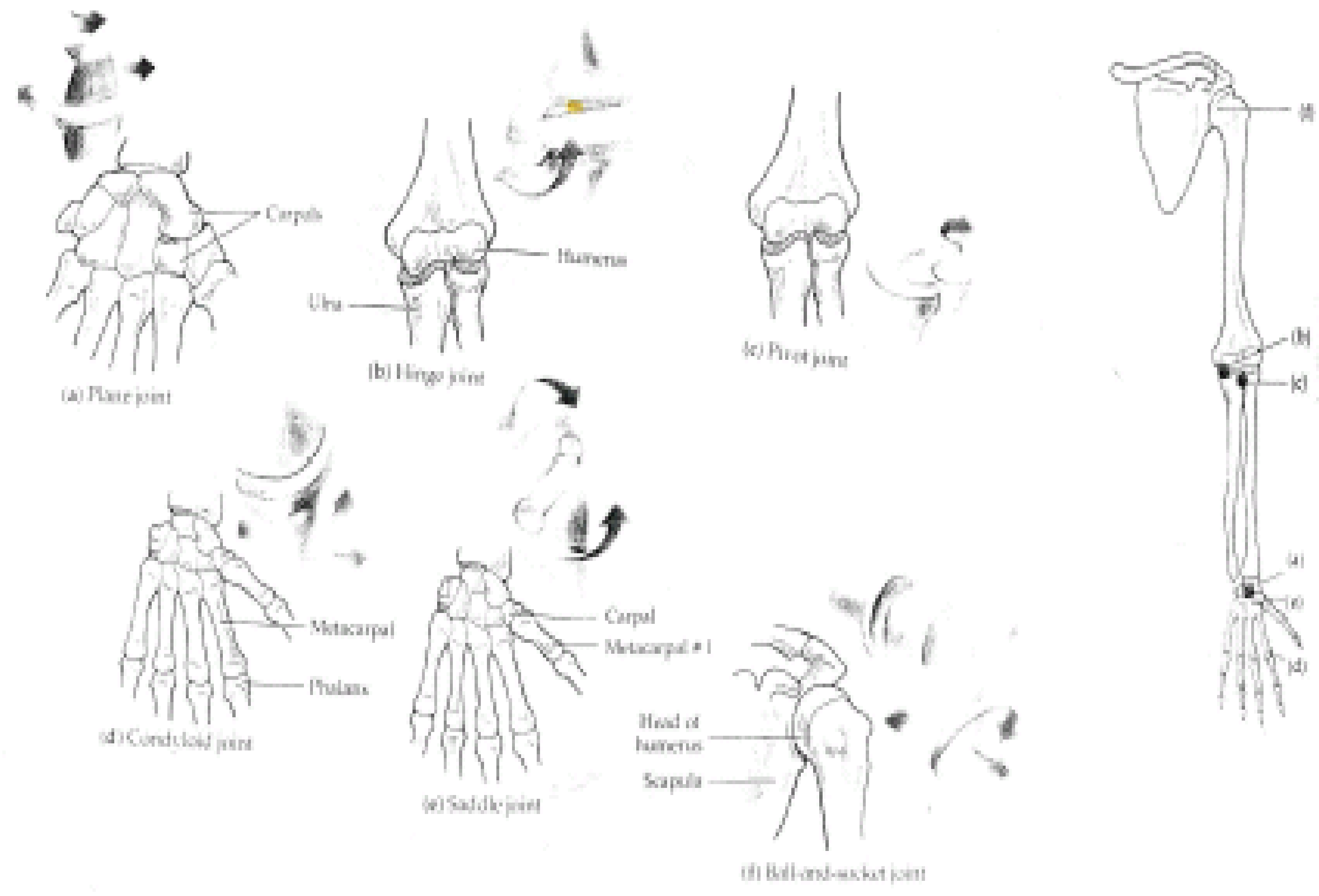
The Human Musculoskeletal System

- In addition to providing support, bones act as levers when the muscles attached to them contract at a joint:

Type of Joint	Example (at intersection)
Plane	Carpals
Hinge	Ulna and Humerus
Pivot	Ulna and Radius
Condyloid	Phalanx and Metacarpal

Types of Joints in the Vertebrate Skeleton

- The vertebrate forelimb provides examples of six types of joints that make many articulations possible
  (arrows indicate movement)



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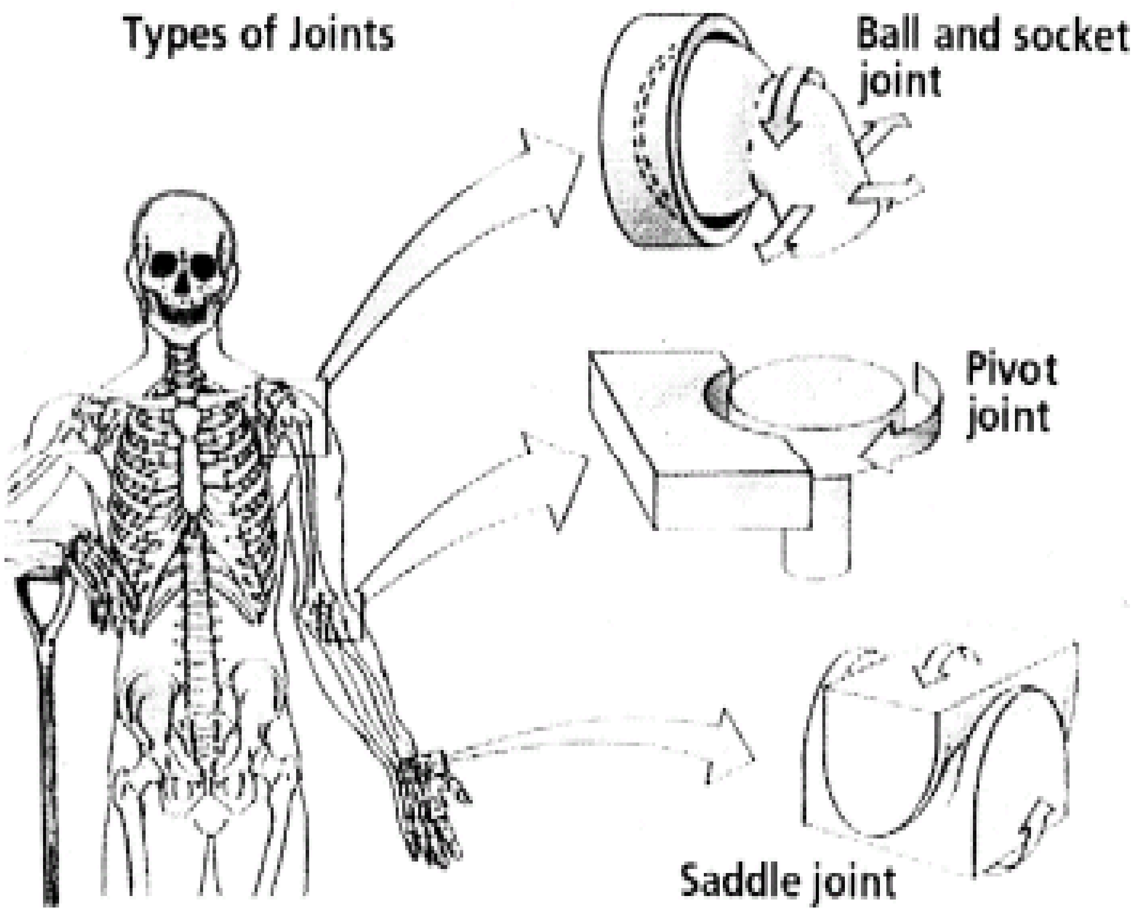
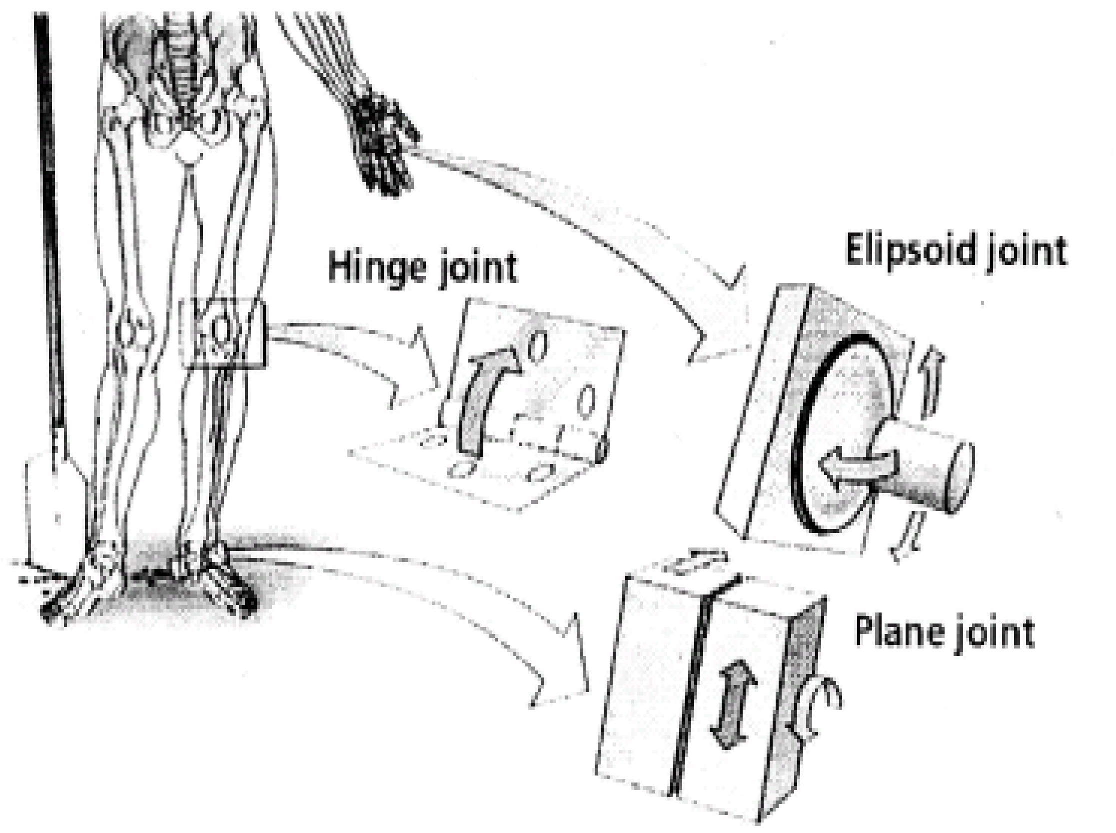


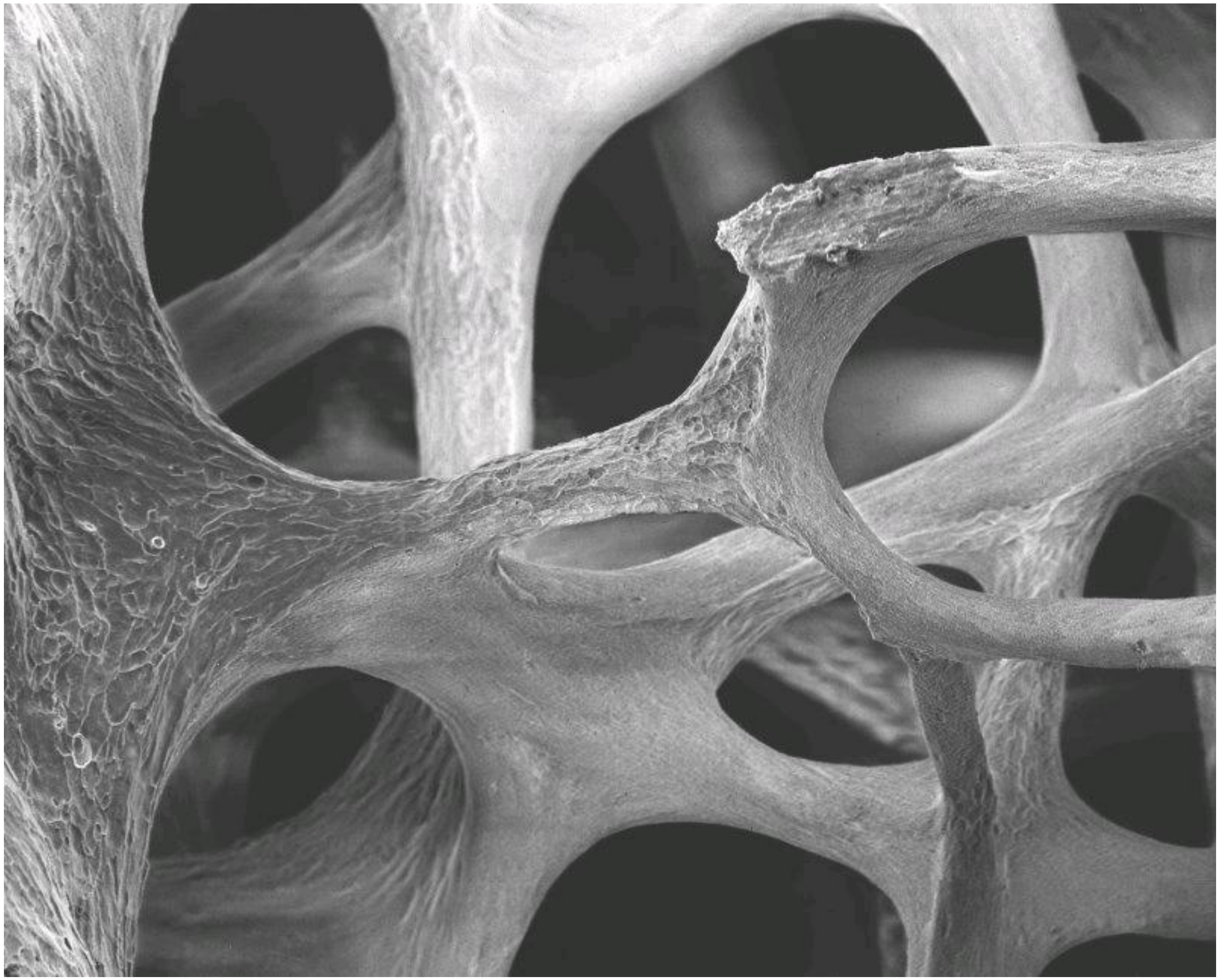
Types of Joints in the Vertebrate Skeleton

- The vertebrate lower limb provides examples of three types of joints that make many articulations possible (arrows indicate movement)



The Structure of Bone

- Bone is a composite material that consists of collagen fibers and hydroxyapatite crystals



This low power scanning electron micrograph shows a section through the third lumbar vertebra of a 71 year old woman; the field of view is about 1 mm wide. Cells and marrow have been removed to reveal bone surfaces. Osteoporotic changes are evident, including extensive fields of resorption pits made by osteoclasts.

Source: http://www.brsoc.org.uk/osteobw.htm

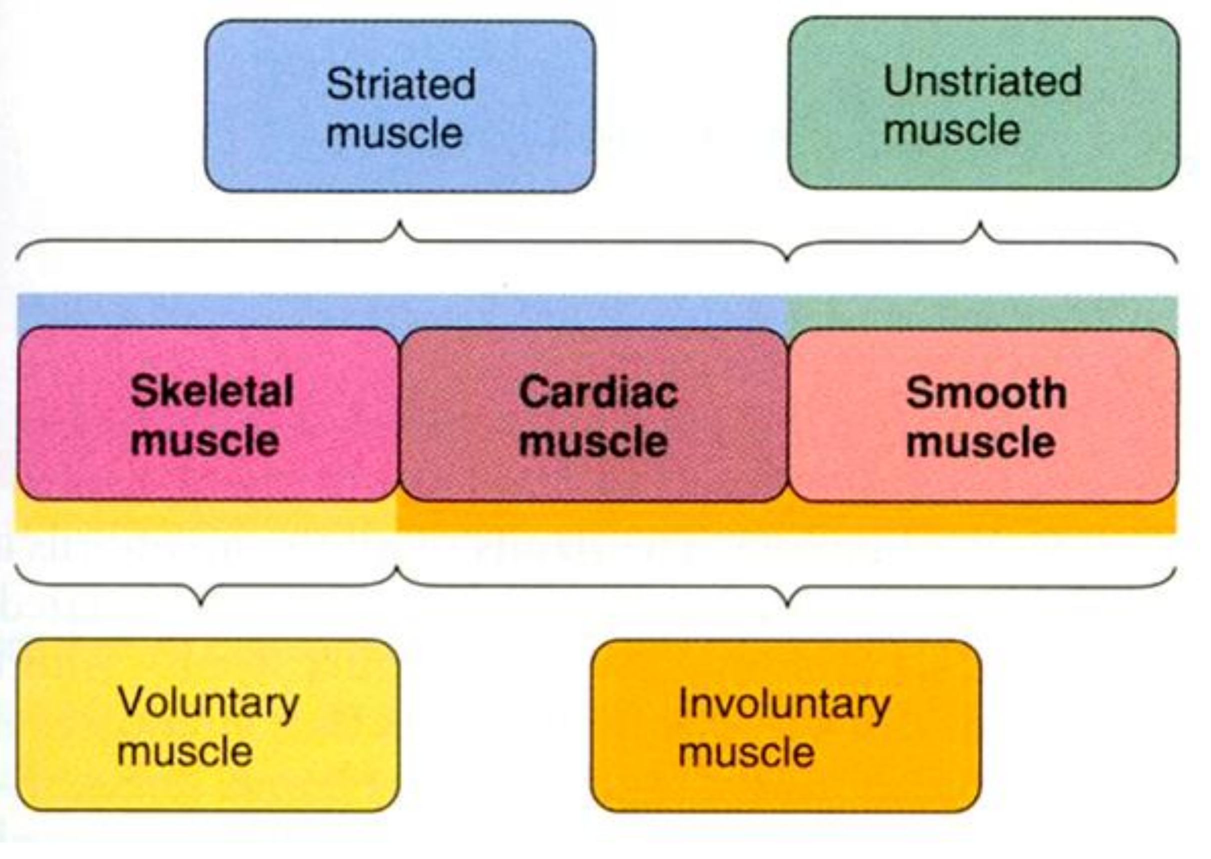
An Introduction to Muscles

- Animal motion is based on the contraction of muscles working against some type of skeleton\
- Three types of muscle exits:

-Muscle is largest group of tissue in body

-Skeletal muscle:
  40% of body weight in men
  32% in women

-Cardiac muscle:
  10% of body weight



An Introduction to Muscles

Muscles: Same functions, different arrangements

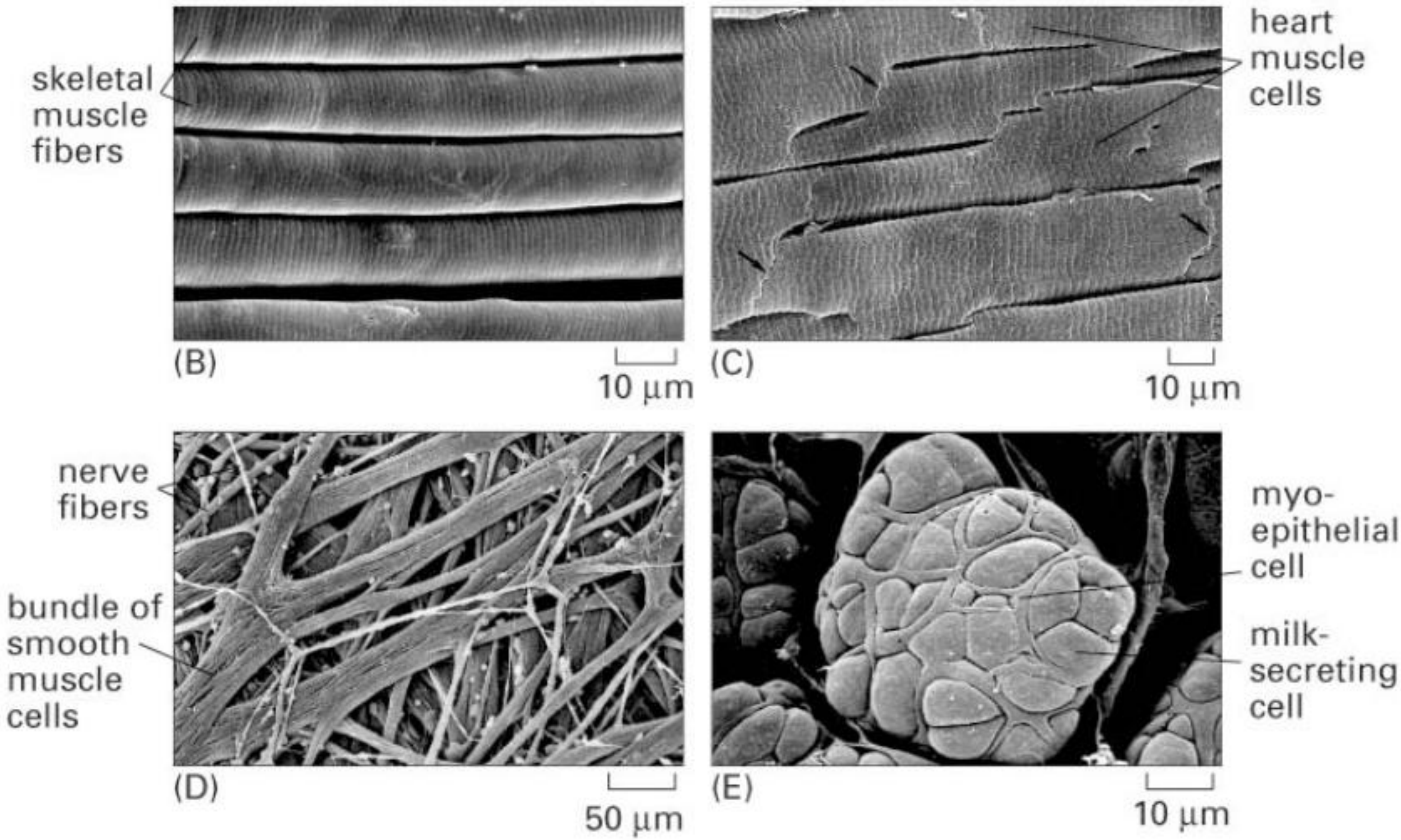


Figure 22–40 part 2 of 2. Molecular Biology of the Cell, 4th Edition.

An Introduction to Muscles

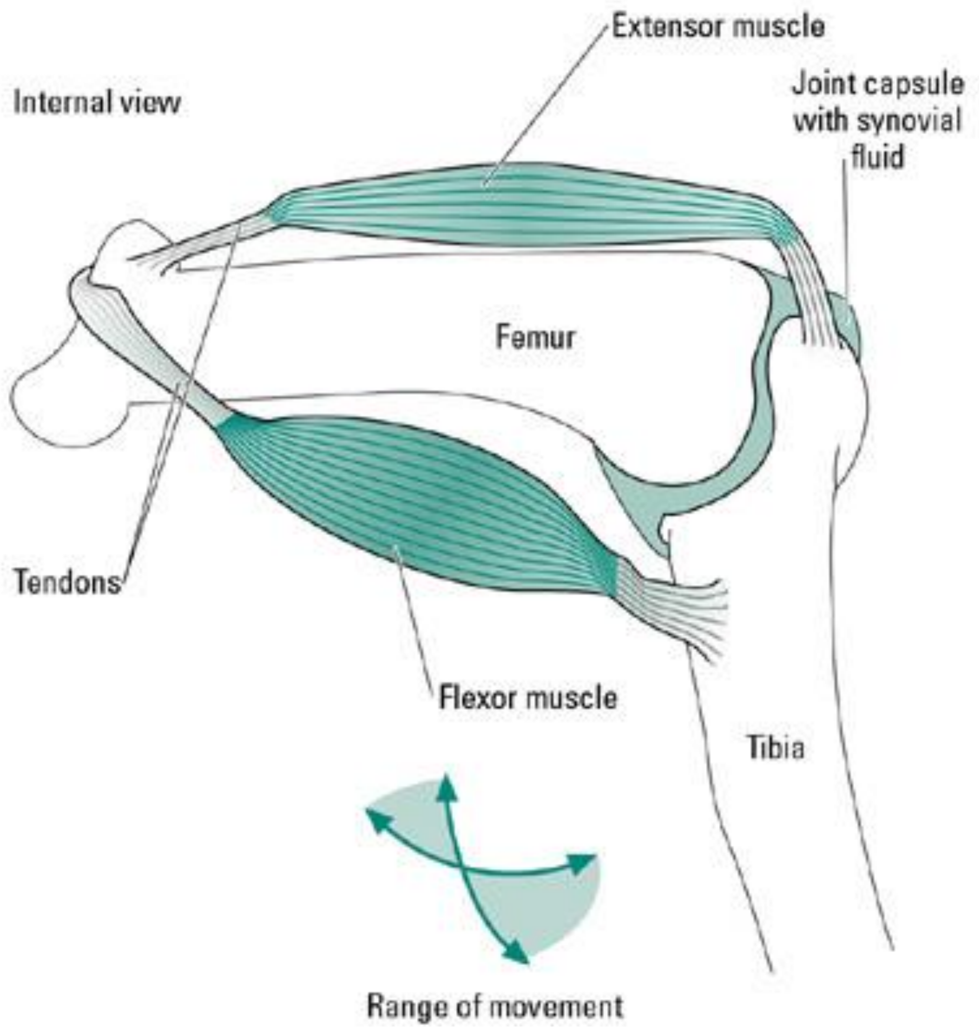
- All muscle work only in contraction:
  - Antagonistic muscle group allows body part to move in opposite directions
  - Requires that skeletal muscle be attached to the body in opposite pairs; with each muscle working against the other

Example:

Flexing an arm involves the contraction of biceps with the hinge joint below the elbow providing a fulcrum of a lever

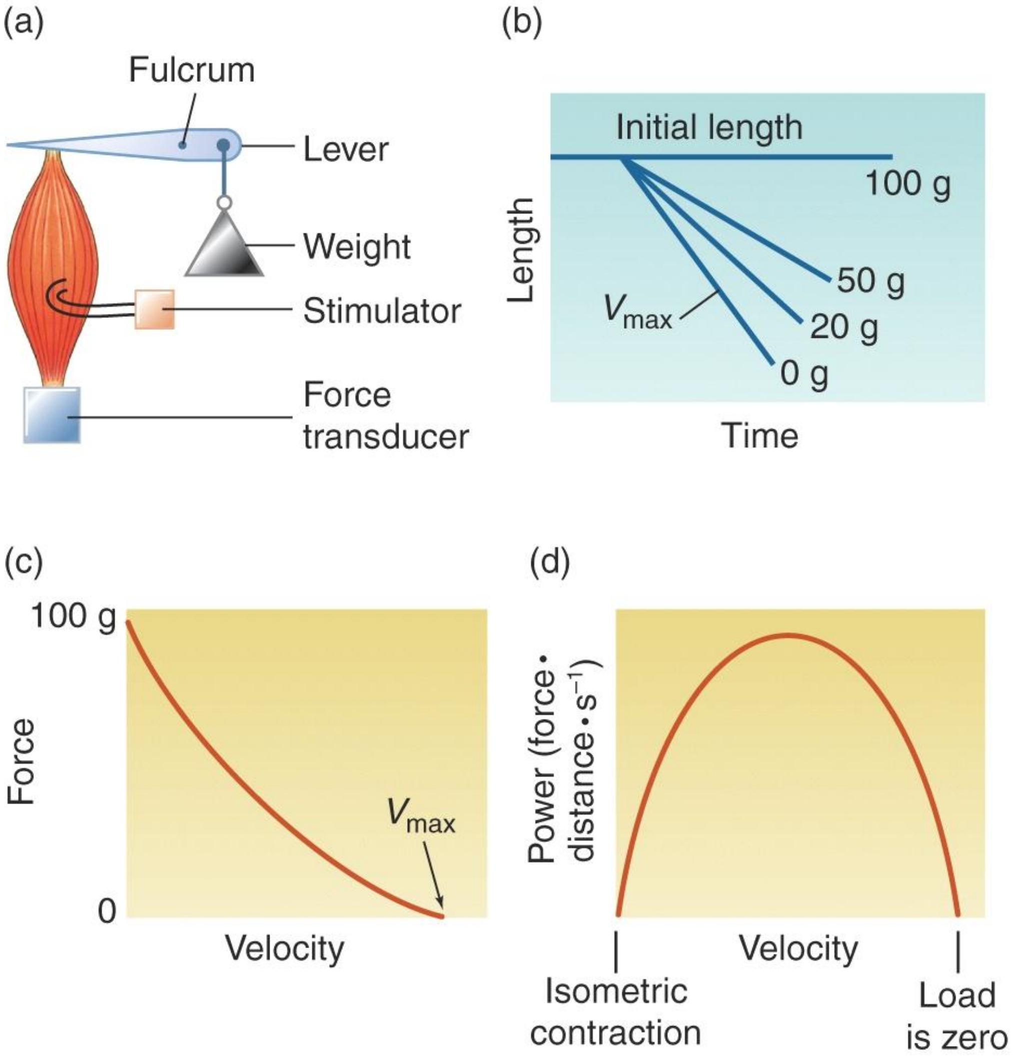
Extending an arm involves the relaxation of biceps while the triceps on the opposite side contracts

The Cooperation of Muscles and Skeletal Movements



The Skeleton as a Lever

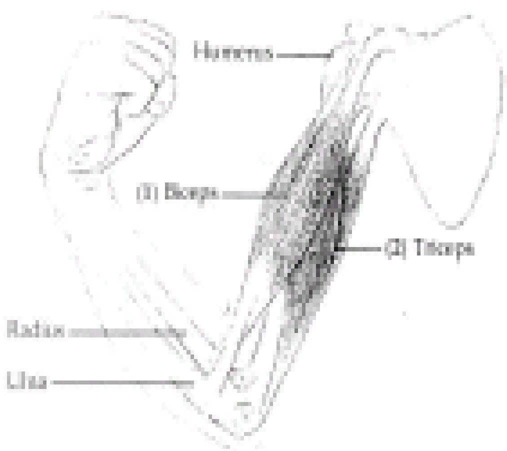
- To raise an object the skeleton acts as a lever
- The muscle applies the load and the lever then pivots about the fulcrum
- An inverse relation between force and velocity exists



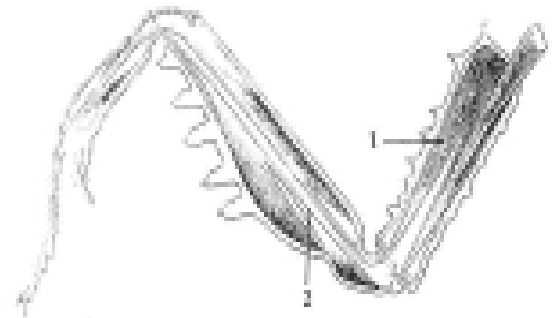
The Skeleton as a Lever

- Contraction of muscles in a human and insects have different results – why?

Raising of Human Arm



Raising/Lowering of Insect Leg



Because of the different positions of the muscles relative to the skeleton

The Structure and Physiology of Vertebrate Skeletal Muscle

- Vertebrate skeletal muscle is attached to bone and responsible for their movements
- Skeletal muscle are characterized by a hierarchy of smaller and smaller parallel units
  - Each muscle is a bundle of long fibers running along the length of the muscle
  - Each Fiber is a single cell with many nuclei
    - Reflecting is formation by many embryonic cells
  - Each fiber itself is a bundle of smaller myofibrils arranged longitudinally
  - Each myofibrils are composed of two types of myofilaments
    - Thin filaments consisting of two strands of actin and one strand of regulatory protein coiled around each other
    - Thick filaments consist of staggered arrays of myosin molecules

The Structure and Physiology of Vertebrate Skeletal Muscle

One nucleus or multi-nucleated

Regular epithelial cells

Muscle cells

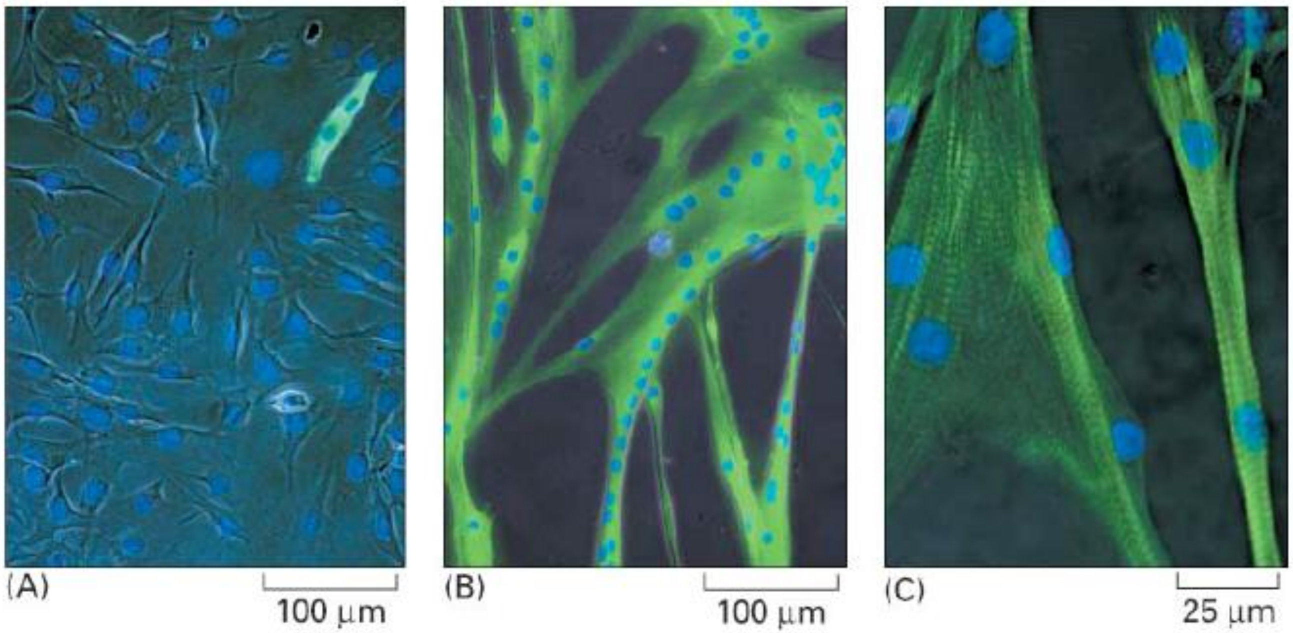
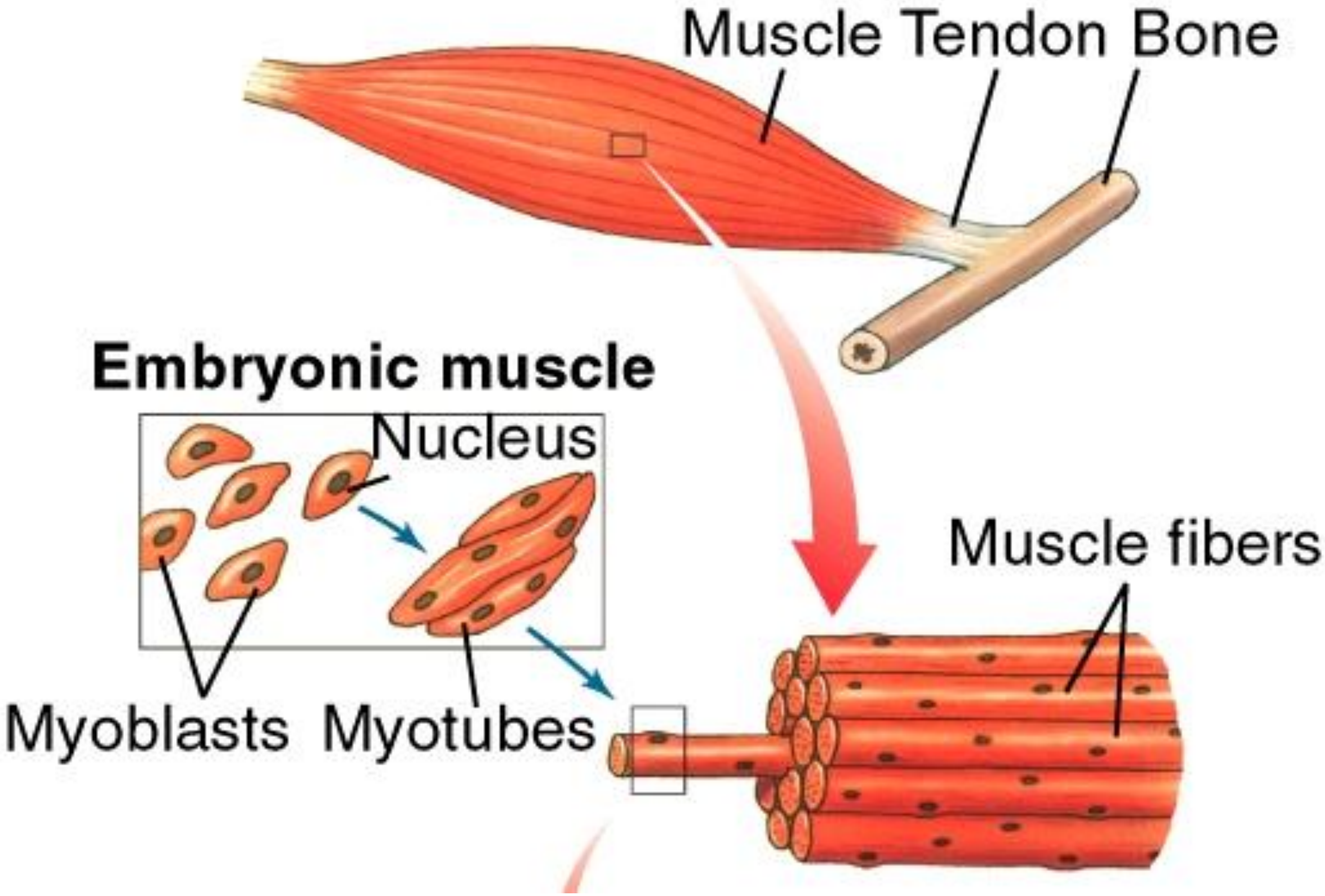


Figure 22–41. Molecular Biology of the Cell, 4th Edition.

The Structure and Physiology of Vertebrate Skeletal Muscle



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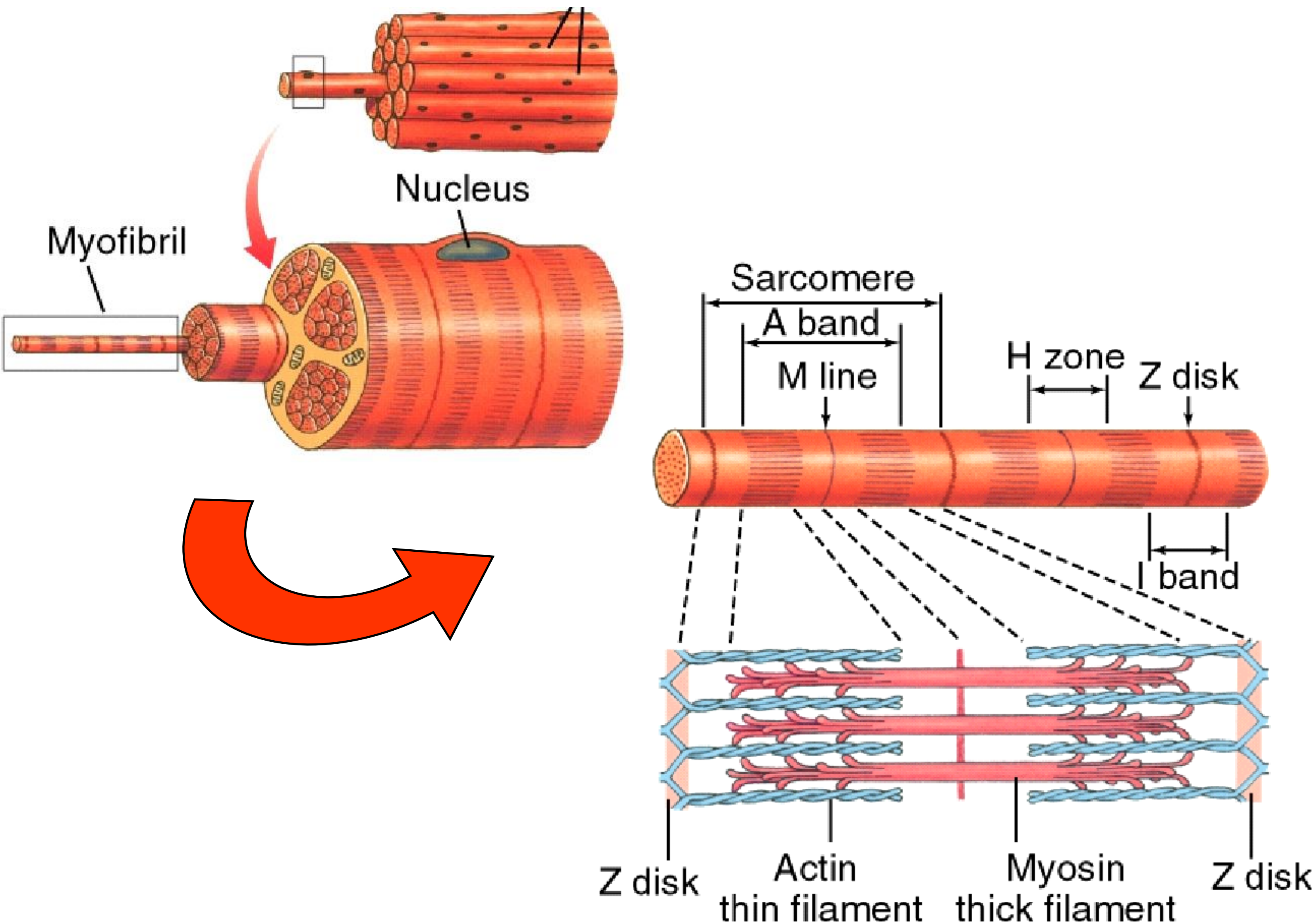
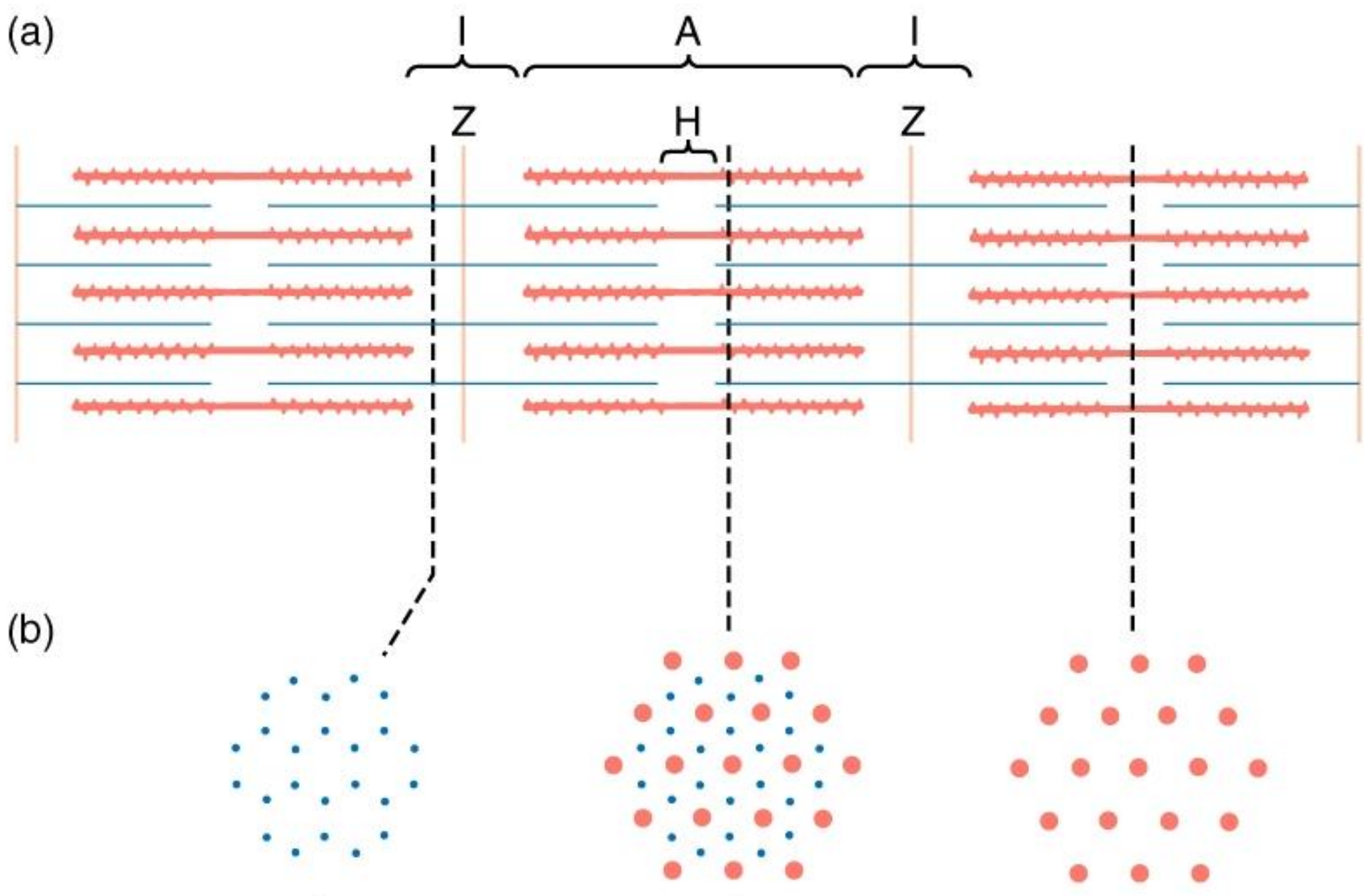


The Structure and Physiology of Vertebrate Skeletal Muscle

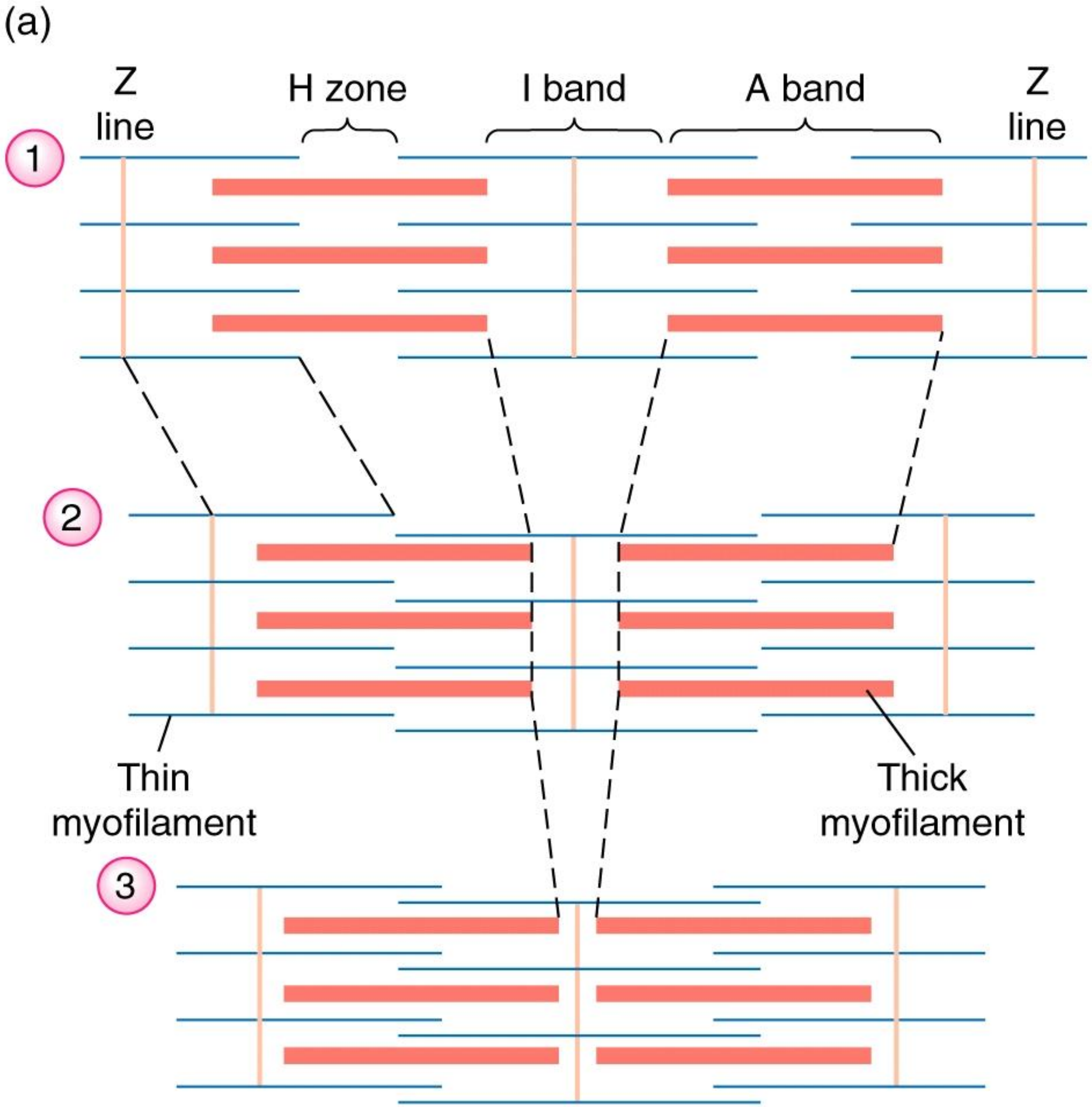
Cross sectional view



Mechanism of Muscle Contraction

- When a muscle contracts: the length of each sacromere is reduced
  - The distance between the Z lines becomes shorter
  - The A band does not change length in the contracted sacromere
- The I band shortens and the H zone disappears
  - Called the Sliding Filament Theory
    - Model proposes that thin and thick filaments do not change length during muscle contractions
    - Filaments slides past each other longitudinally
    - Sliding increases the degree of overlap between thin and thick filaments
    - Due to overlap the overall length occupied by thick and thin filaments must decrease

Mechanism of Muscle Contraction



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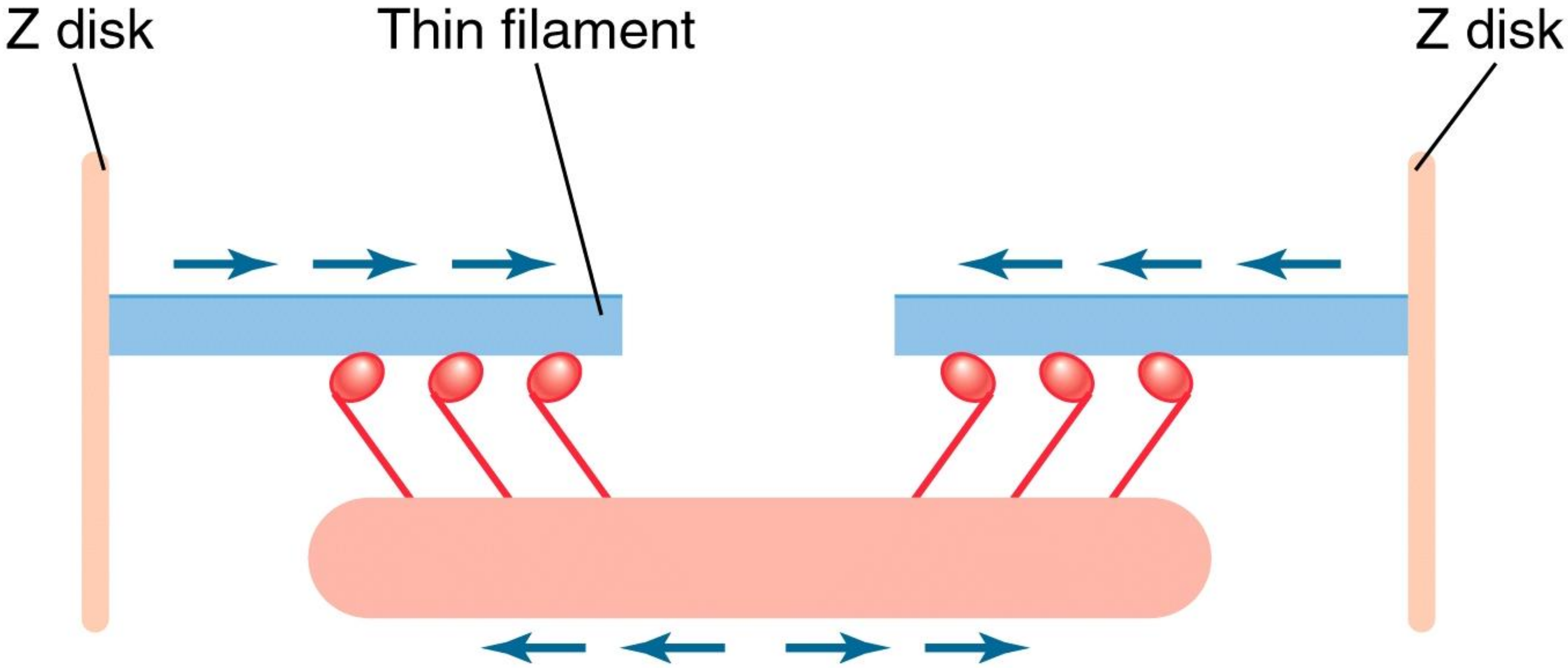
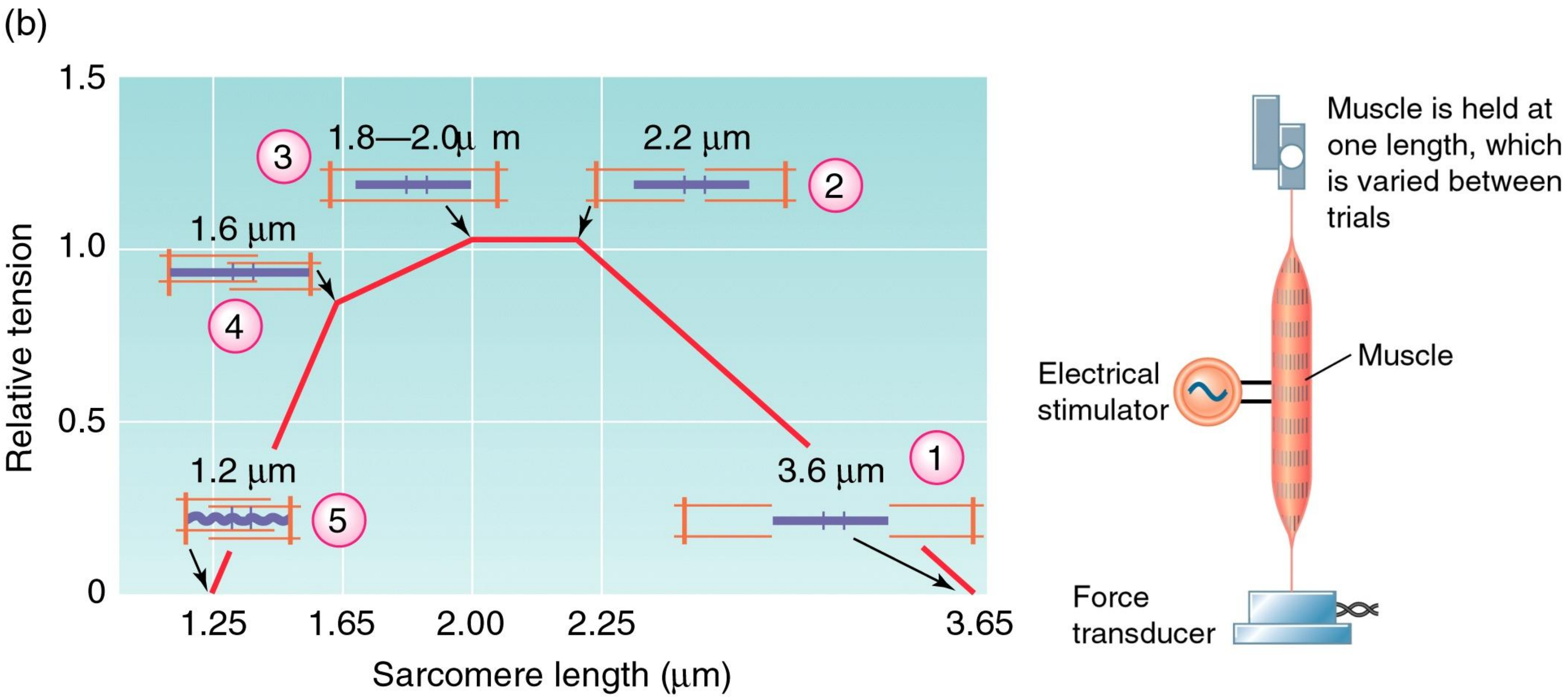


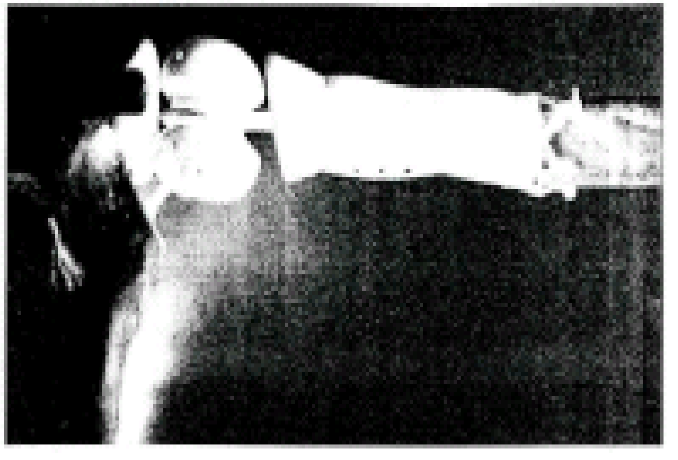
Mechanism of Muscle Contraction



History of Biomaterials

- The Romans, Chinese and Aztec used gold in dentistry more than 2000 year ago
- Glass eyes and wooden teeth have been in use throughout much of history
- Modern prosthetic devices can be traced back to France in the 19th century (pre-septic and post septic eras)

Example of Early Implant



The Development of Biomaterials and Prosthesis in the 20th Century

- Synthetic plastics became available during the early 20th century
- PMMA Poly (methyl methacrylate) was introduced into dentistry in 1937
- Shards of PMMA unintentionally introduced into the eyes of aviators from gunnery in W.W.II
- suggested only a mild foreign body reaction
- Charnley in the 1960s used PMMA, UHMWPE, and stainless steel for total hip replacement before the term 'biomaterials' was coined
- The term 'biomaterial' emerged from early Clemson University biomaterials symposia in the late 1960s and the early 1970s

The Evolution of Multidisciplinary Biomaterials

- The early work was dominated by individual physician visionaries who implanted various materials to find solutions to medical problems that were often life threatening
- However the Clemson symposia brought together researchers and engineers with a wide range of backgrounds to explore the nature of biocompatibility
- This led ultimately to the development of the field of biomaterials sciences and engineering
- The Society of Biomaterials was created in 1975
- Academic departments and numerous companies have also developed around this new field

The Scope of Biomaterials Science

- Biomaterials are used primarily in medical and dental applications
- However they are also used to grow cells in culture
- in apparatus for handling proteins in the lab
- in devices to regulate fertility in cattle
- and could possibly be used in cell-silicon biochips in computers
- The common theme is the interaction between biological systems and synthetic (or modified natural) materials

Introduction to Biomedical Devices and Biomaterial Science

- Biomedical devices are man-made systems that are used to supplement or replace the functions of biological systems

Example Systems	Machined form:
Heart Valves	Carbons, Metals, Elastomers, Fabrics, Pig Valves
Artificial Hip Joints	Titanium Alloys, High Strength Alloys, Ceramics
Dental Implants	Titanium Alloys, Ceramics, Composites
Intraocular Lenses	PMMA, Silicone, Elastomers

- Key issue: Biocompability
  - Limits the usable lifetime of the system
- Modern biomaterials science is the study of the application of materials to solve problems in biology and medicine

Basic Definitions

- Biomaterial:
  - A material used in a device, intended to interact with biological systems (Williams, 1987)
    - N.B. the term “medical device” is not used in the definition in order to broaden the scope of the definition/application

- Biocompatibility:
  - Term used to describe the ability of a material to perform with an appropriate host response in a specific application (Williams, 1987)

Some Examples of Synthetic and Natural Materials Used in Medicine

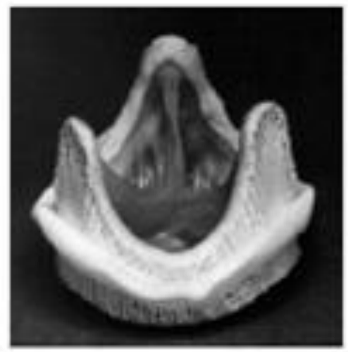
TABLE 1 Some Applications of Synthetic Materials and Modified Natural Materials in Medicine

Application	Types of materials
Skeletal system	
Joint replacements (hip, knee)	Titanium, Ti–Al–V alloy, stainless steel, polyethylene
Bone plate for fracture fixation	Stainless steel, cobalt–chromium alloy
Bone cement	Poly(methyl methacrylate)
Bony defect repair	Hydroxylapatite
Artificial tendon and ligament	Teflon, Dacron
Dental implant for tooth fixation	Titanium, alumina, calcium phosphate
Cardiovascular system	
Blood vessel prosthesis	Dacron, Teflon, polyurethane
Heart valve	Reprocessed tissue, stainless steel, carbon
Catheter	Silicone rubber, Teflon, polyurethane
Organs	
Artificial heart	Polyurethane
Skin repair template	Silicone–collagen composite
Artificial kidney (hemodialyzer)	Cellulose, polyacrylonitrile
Heart–Lung machine	Silicone rubber
Senses	
Cochlear replacement	Platinum electrodes
Intraocular lens	Poly(methyl methacrylate), silicone rubber, hydrogel
Contact lens	Silicone–acrylate, hydrogel
Corneal bandage	Collagen, hydrogel

Case Study: Heart Valves

- Motivation: Degeneration of the heart caused by diseases make repair or replacement necessary
  - Heart valves prostheses are fabricated for durability and reduction in immunological reactivity; these include:

Carbons



Fabric

Pig valves

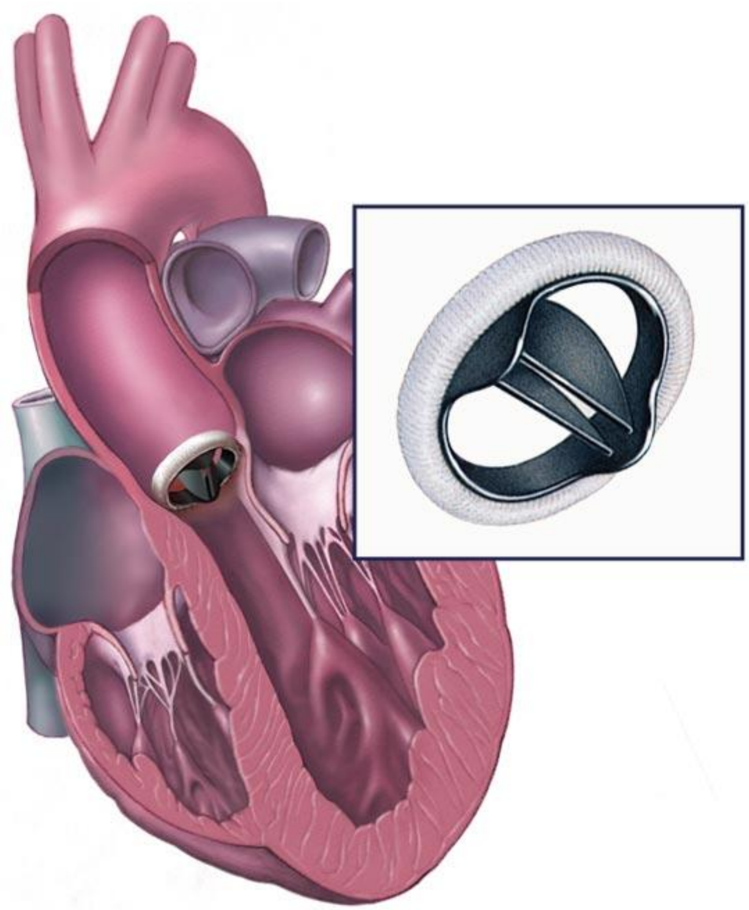
Metal

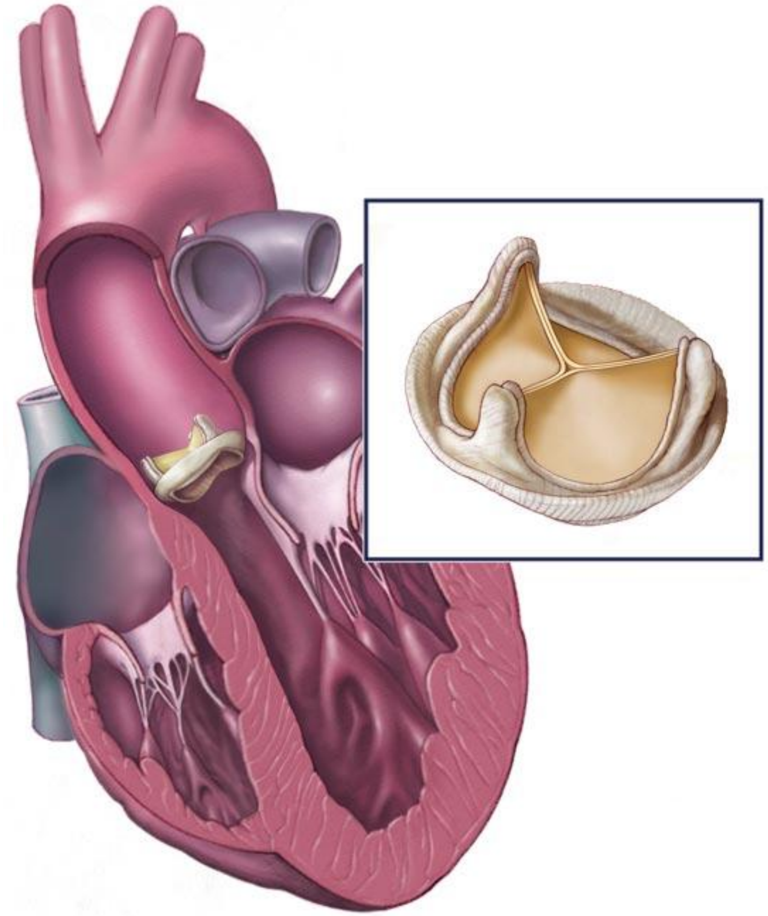
Metal/Carbon

Elastomers

Case Study: Heart Valves

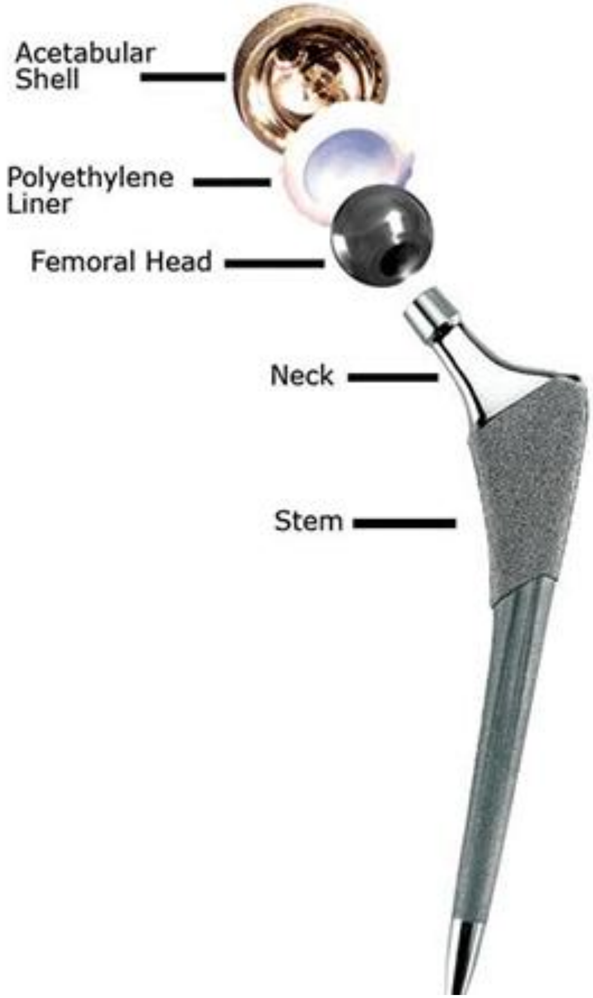
- More than 45 000 heart valve replacement are implanted each year in the USA
- Recipients of heart valves must be on blood thinners





Case Study: Artificial Hip Joints

- Motivation: Degenerative damage caused by cyclic mechanical stress and/or rheumatological disease lead to wear of natural joints
  - If not treated, can lead to complete loss of mobility and intense pain
- Artificial hip joints are subject to high mechanical stresses and undergo considerable amount of mechanical abuse
- More than 90 000 hip joints replacement surgeries are completed each year

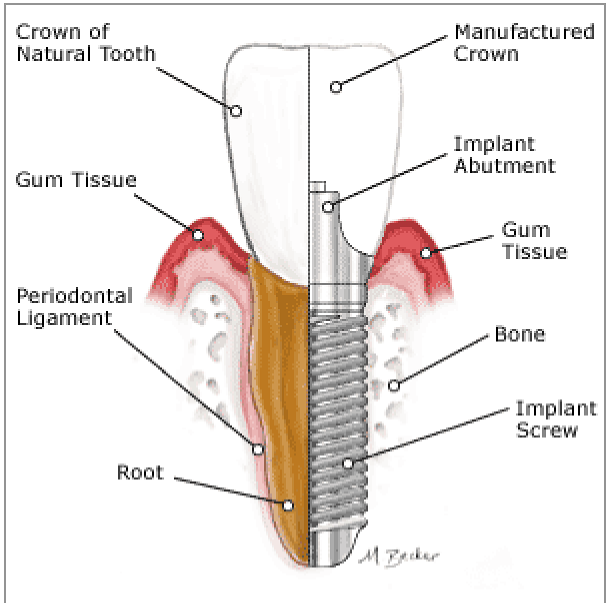


Case Study: Artificial Hip Joints

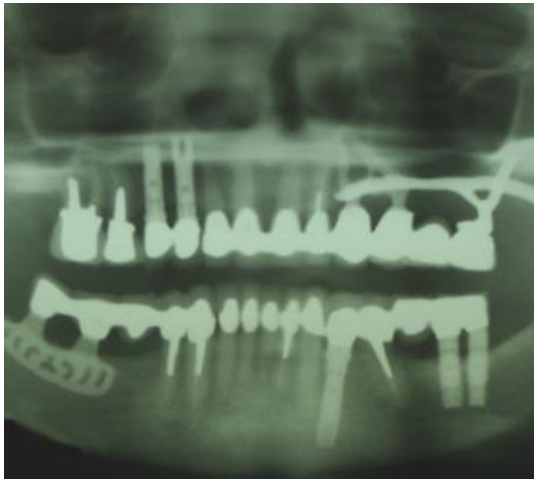
- Structure and Function:
  - Artificial hip joints are fabricated from titanium alloys (Ti-6Al-4V), Co-Cr alloys, UHMWPE, ceramics, and composites
  - Some ambulatory function are restored within few days after surgery; however, a good healing-in period is required for the attachment to develop between bone and implant

Case Study: Dental Implants

- Motivation: Multiple disease can cause tooth decay that lead to complete loss of tooth
  - The end of the 20th century, saw a widespread introduction of Ti Implants and ceramic crowns that revolutionized dentistry
    - Ti devices are implanted into 275 000 patients every year in the USA with some individuals receiving more than 12 implants
    - Ceramic crowns (glass ceramics + alumna, mica, or leucite) are also implanted into numerous people each year

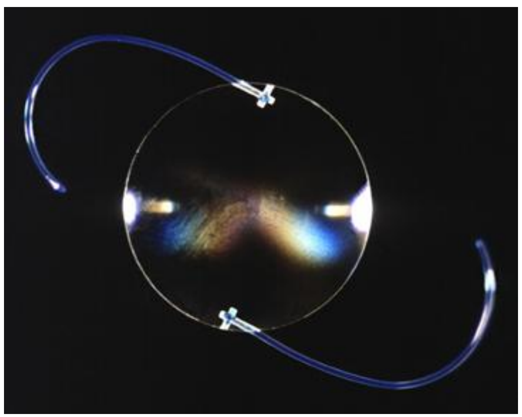


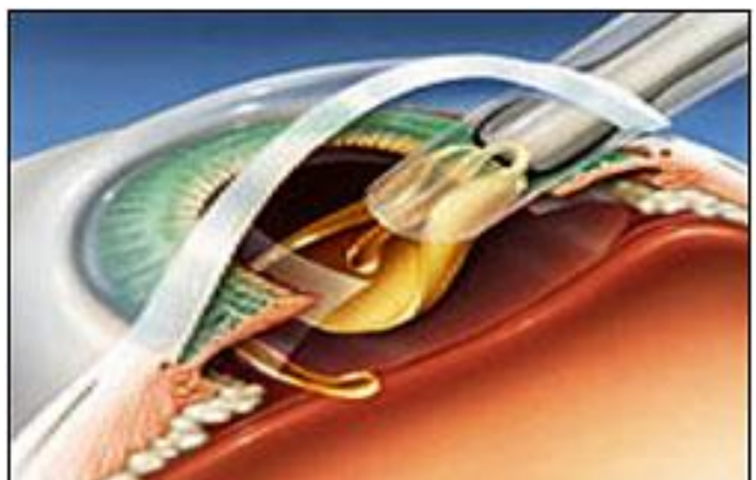
Parts of an Implant



Case Study: Intraocular Lenses

- Motivation: After removal of cataracts, artificial lens is needed to focus the light on the retina
  - Intraocular lenses are made of poly(methyl metharcrylate), silicone
  - By the age of 75, more than 50% of the population in the US suffers from cataracts that could benefit from intraocular lenses
  - Currently about 1.4 million patients have this surgery in the US





General Observation on Implant

- Implants are generally successful in above examples
- Also a wide range of materials are used due to broad range of chemical, physical, and mechanical properties required
- Implants are used in a diverse range of anatomical sites
- Mechanisms by which body responds to foreign bodies are observed in each case
- Problems, concerns, and unexplained observations are observed for each device (regulation by the FDA)
- Nevertheless companies are manufacturing these devices and making a profit

Magnitude of the Field

- Magnitude of need and magnitude of commercial market
- Each contact lens may sell for $100 with
  - 1.4 million implants being implanted in the U.S. each year
  - 20 million contact lenses are purchased each year
- Each hip implant sells for $3000 with
  - 90,000 implants being implanted in the U.S. cach year
  - 500,000 hip prostheses are implanted in the world each year
- There are 100,000 heart valves sold worldwide each year
- Some concerns and unexplained reactions are observed for each device
- Conflict of interest can arise between commercial interest and ethical considerations