Skeletal Muscle

- **skeletal muscle** - voluntary, striated muscle attached to one or more bones
- **striations** - alternating light and dark transverse bands
  - results from an overlapping of internal contractile proteins
- **voluntary –** usually subject to conscious control
- **muscle cell**, **muscle fiber**, (**myofiber**) as long as 30 cm

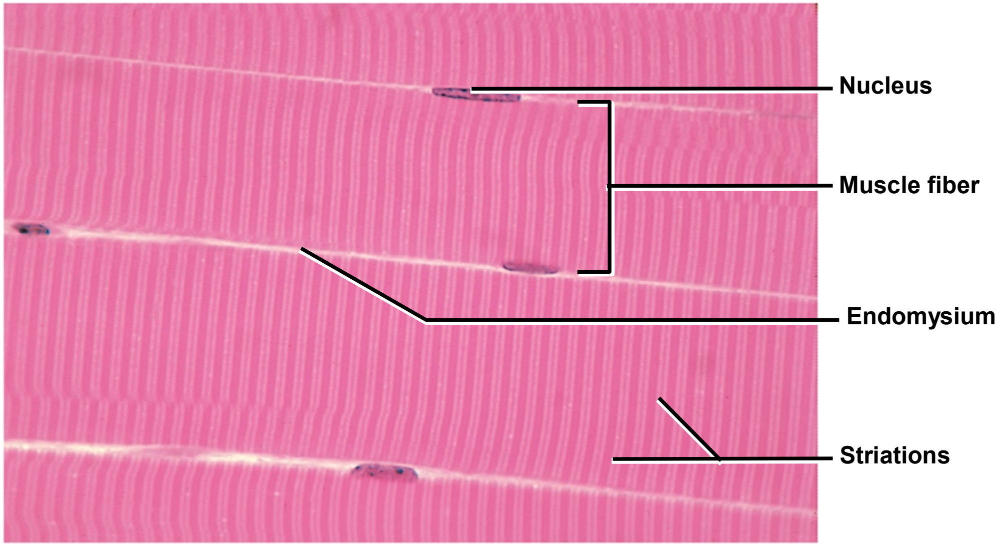

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Figure 11.1

Structure of a Skeletal Muscle Fiber

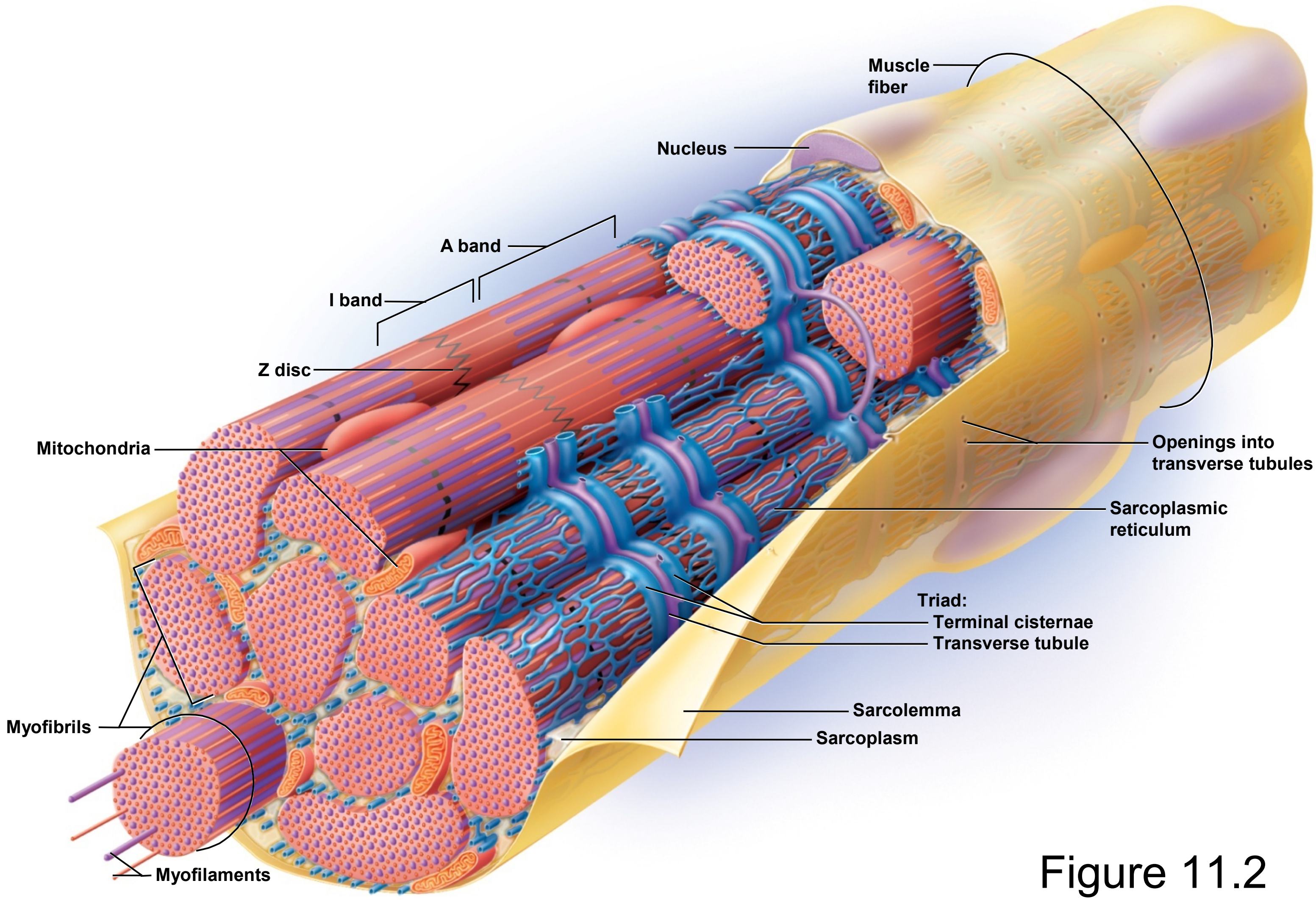
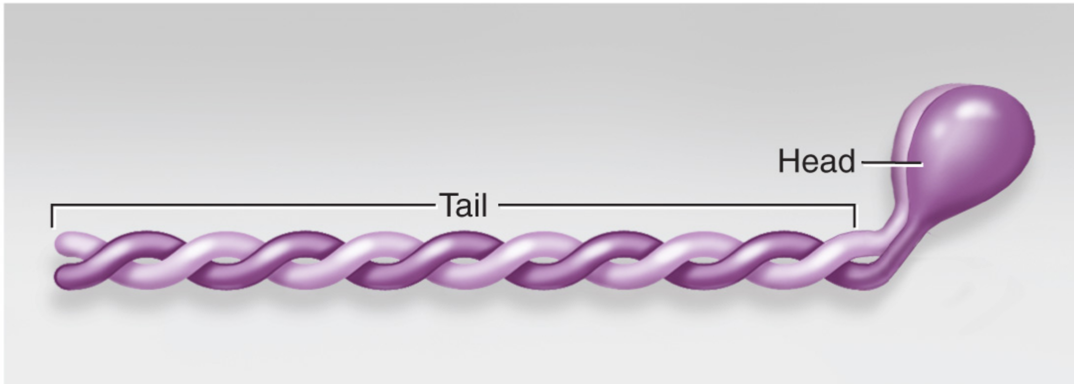


Figure 11.2

The Muscle Fiber

- **sarcolemma** – plasma membrane of a muscle fiber
- **sarcoplasm** – cytoplasm of a muscle fiber
- **myofibrils** – long protein bundles that occupies the main portion of the
  sarcoplasm
  - **glycogen** – stored in abundance to provide energy with heightened exercise
  - **myoglobin** – red pigment – stores oxygen needed for muscle activity
- **sarcoplasmic reticulum** (SR) - smooth ER that forms a network around each myofibril – **calcium reservoir**
  - calcium activates the muscle contraction process

Thick Myofilaments



(a) Myosin molecule

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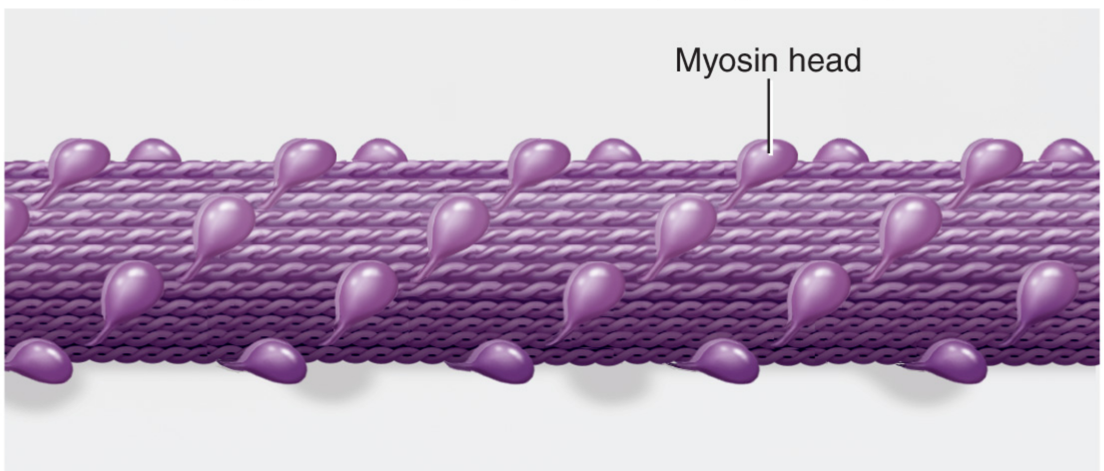
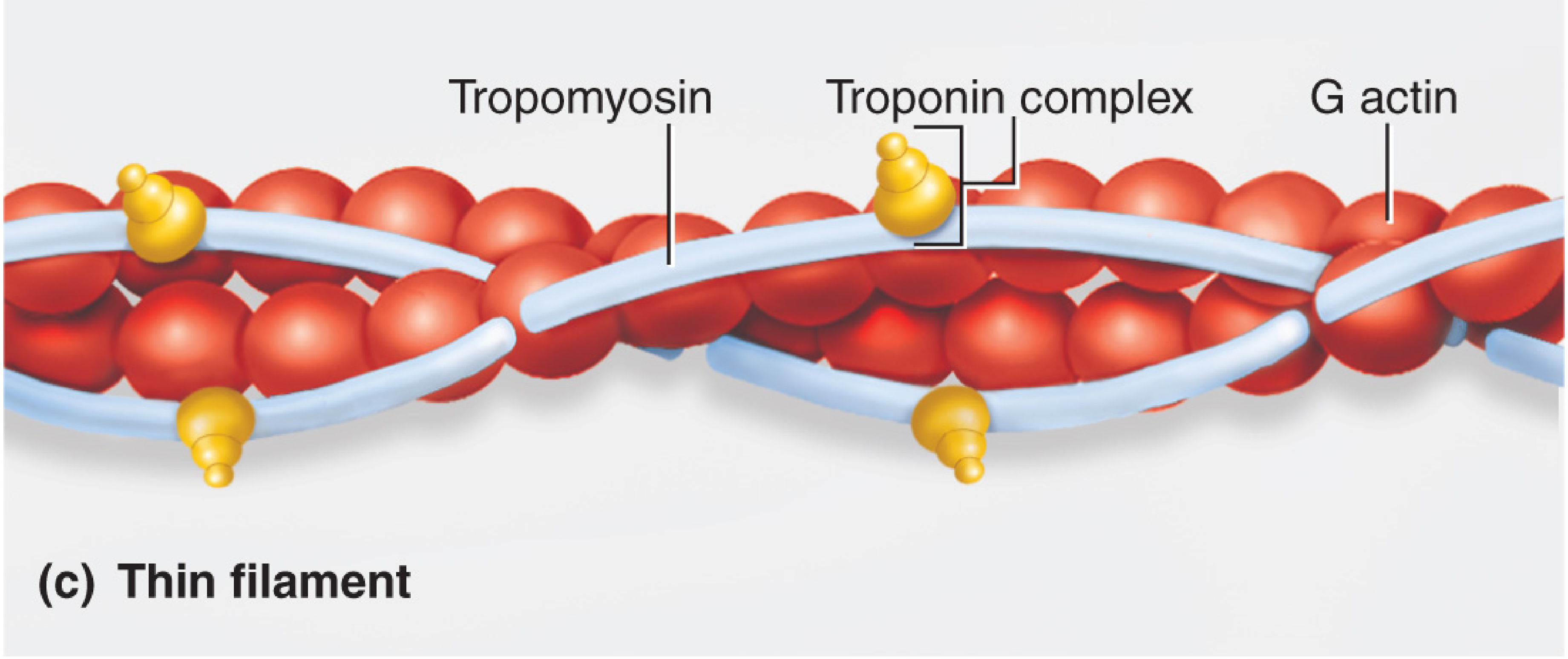
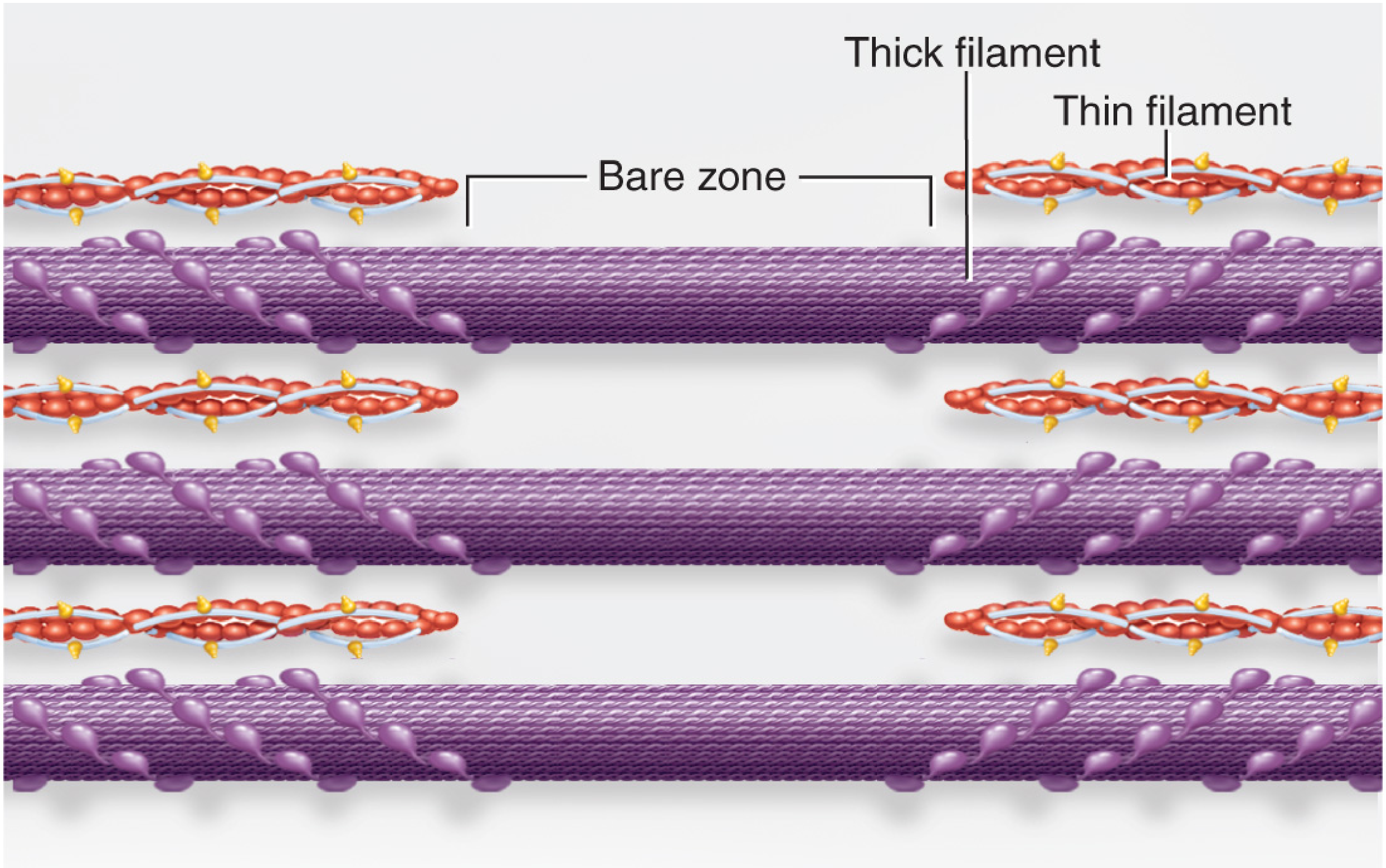


(b) Thick filament

Thin Myofilaments



Overlap of Thick and Thin Filaments

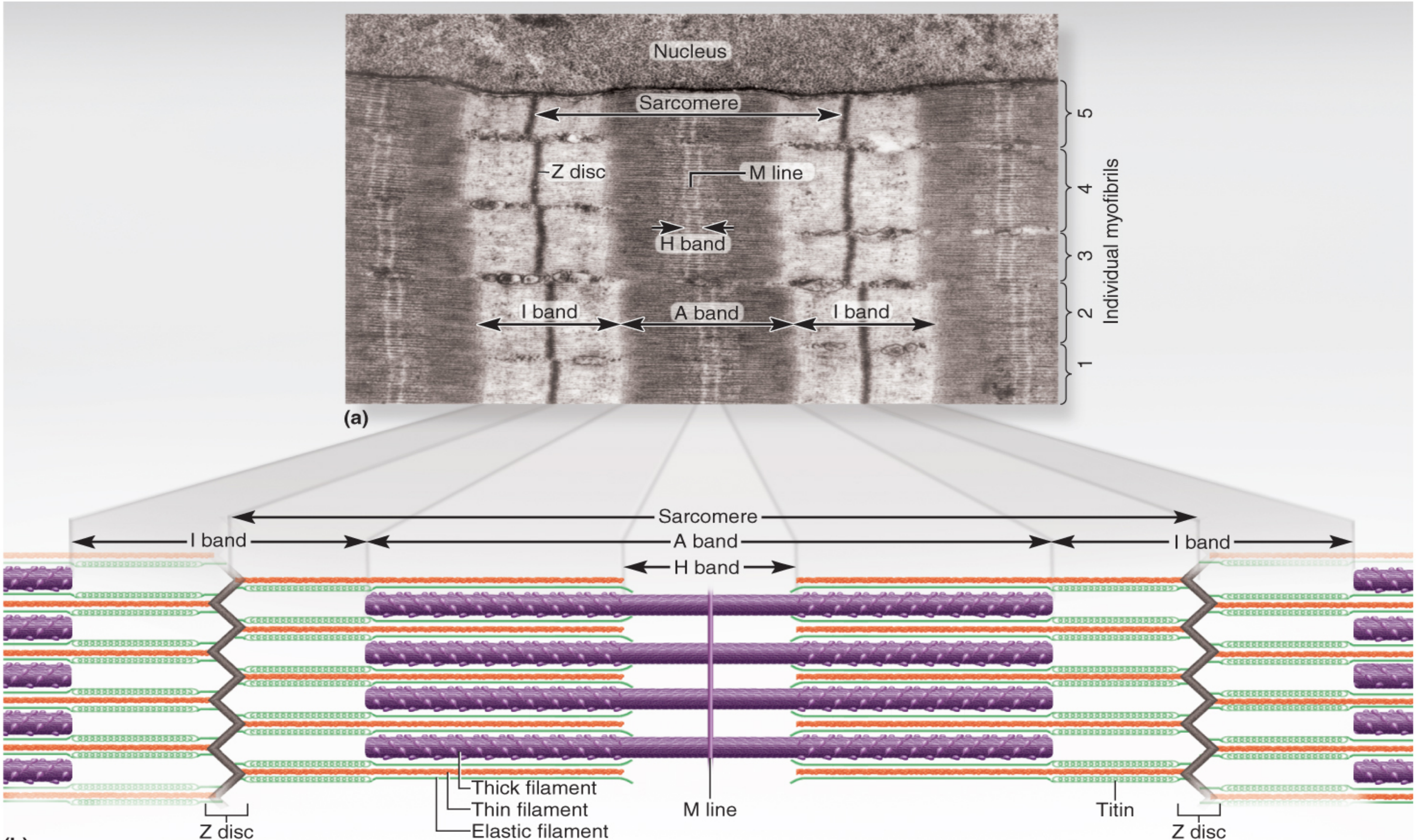


(d) Portion of a sarcomere showing the overlap of thick and thin filaments

Regulatory and Contractile Proteins

- **contractile proteins - myosin and actin**
  - do the work
- **regulatory proteins - tropomyosin and troponin**
  - a switch that determine when the fiber can contract and when it cannot
  - contraction activated by release of calcium into sarcoplasm and its binding to troponin,
  - troponin changes shape and moves tropomyosin off the active sites on actin

Striations



(Top): Visuals Unlimited

Sarcomeres

- **sarcomere** - segment from Z disc to Z disc
  - functional contractile unit of muscle fiber
- muscle cells shorten because their individual sarcomeres shorten
  - Z disc (Z lines) are pulled closer together as thick and thin filaments slide past each other
- neither thick nor thin filaments change length during shortening
  - only the amount of overlap changes
- during shortening dystrophin & linking proteins also pull on extracellular proteins
  - transfers pull to extracellular tissue

Accessory Proteins

- **dystrophin** – most clinically important
  - links actin in outermost myofilaments to transmembrane proteins and eventually to fibrous endomysium surrounding the entire muscle cell
  - transfers forces of muscle contraction to connective tissue around muscle cell
  - genetic defects in dystrophin produce disabling disease **muscular dystrophy**

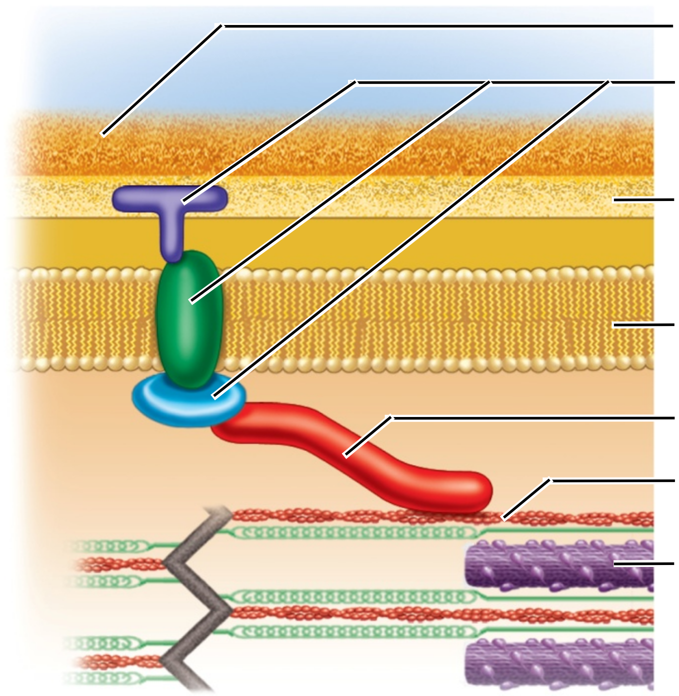
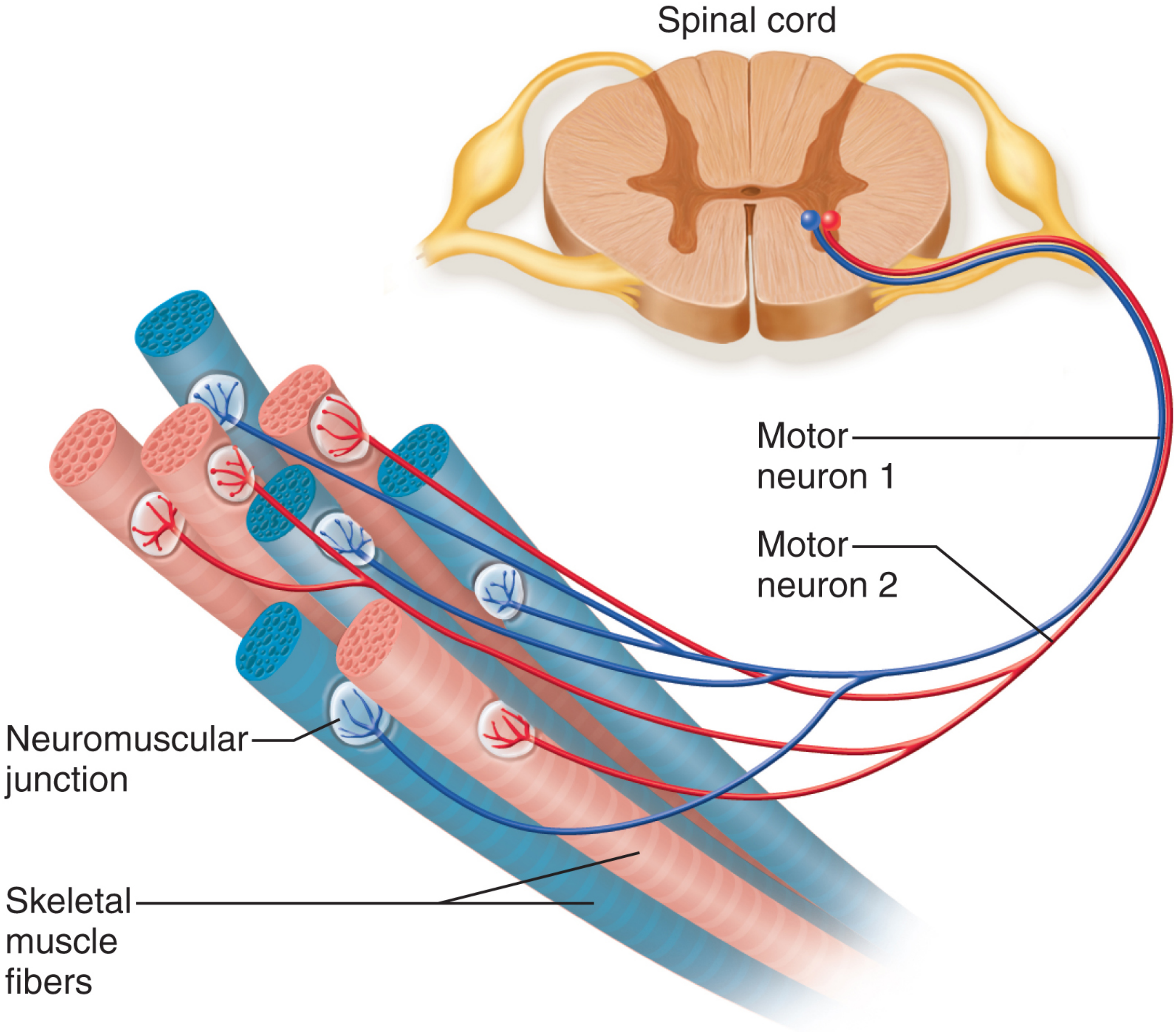


Figure 11.4

The Nerve-Muscle Relationship

- **somatic motor neurons** – nerve cells whose cell bodies are in the brainstem and spinal cord that serve skeletal muscles
- **somatic motor fibers** –their **axons** that lead to the skeletal muscle
  - each nerve fiber branches out to a number of muscle fibers
  - each muscle fiber is supplied by only one motor neuron


Spinal cord
Motor neuron 1
Motor neuron 2
Neuromuscular junction
Skeletal muscle fibers

Motor Units

- **motor unit** – one nerve fiber and all the muscle fibers innervated by it

- **muscle fibers of one motor unit**
  - dispersed throughout the muscle
  - contract in unison
  - produce weak contraction over wide area
  - provides ability to sustain long-term contraction as motor units take turns contracting (postural control)
  - effective contraction usually requires the contraction of several motor units at once

- **average motor unit** – 200 muscle fibers for each motor unit

- **small motor units** - fine degree of control
  - 3-6 muscle fibers per neuron
  - eye and hand muscles

- **large motor units** – more strength than control
  - powerful contractions supplied by large motor units – gastrocnemius – 1000 muscle fibers per neuron
  - many muscle fibers per motor unit

The Neuromuscular Junction

- **synapse** – point where a nerve fiber meets its target cell
- **neuromuscular junction (NMJ) -** when target cell is a muscle fiber
- one nerve fiber stimulates the muscle fiber at several points within the NMJ

Neuromuscular Junction - LM

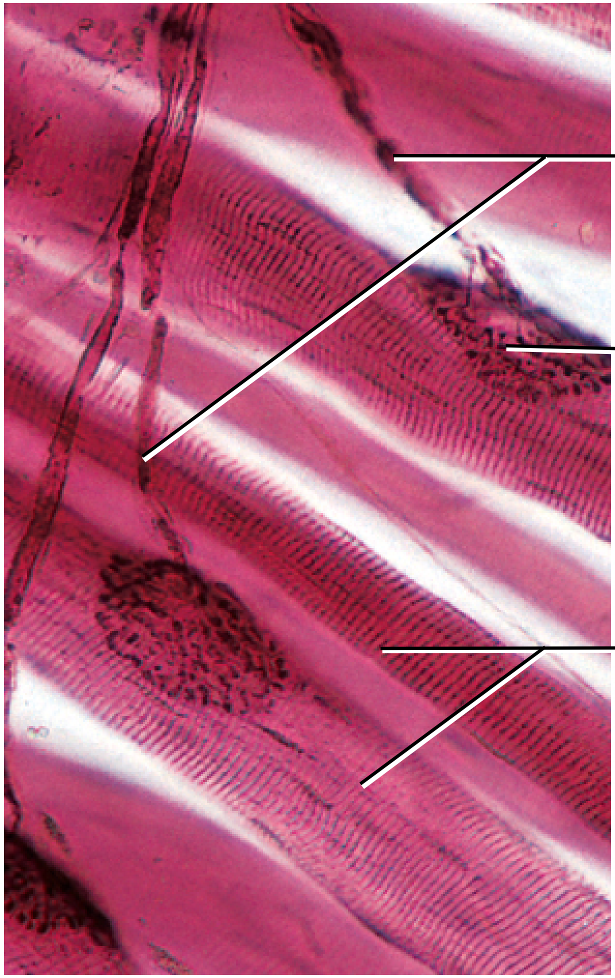


Figure 11.7a

Victor B. Eichler

Components of Neuromuscular Junction

- **synaptic knob** - swollen end of nerve fiber
  - contains **synaptic vesicles** filled with **acetylcholine** (ACh)
- **synaptic cleft** - tiny gap between synaptic knob and muscle sarcolemma
- **Schwann cell** envelops & isolates all of the NMJ from surrounding tissue fluid
- synaptic vesicles undergo **exocytosis** releasing ACh into synaptic cleft
- 50 million **ACh receptors** – proteins incorporated into muscle cell plasma membrane
  - **junctional folds** of sarcolemma beneath synaptic knob
    - increases surface area holding ACh receptors
      - lack of receptors leads to paralysis in disease myasthenia gravis
- **basal lamina** - thin layer of collagen and glycoprotein separates Schwann cell and entire muscle cell from surrounding tissues
  - contains **acetylcholinesterase** (AChE) that breaks down ACh after contraction causing relaxation

Neuromuscular Junction

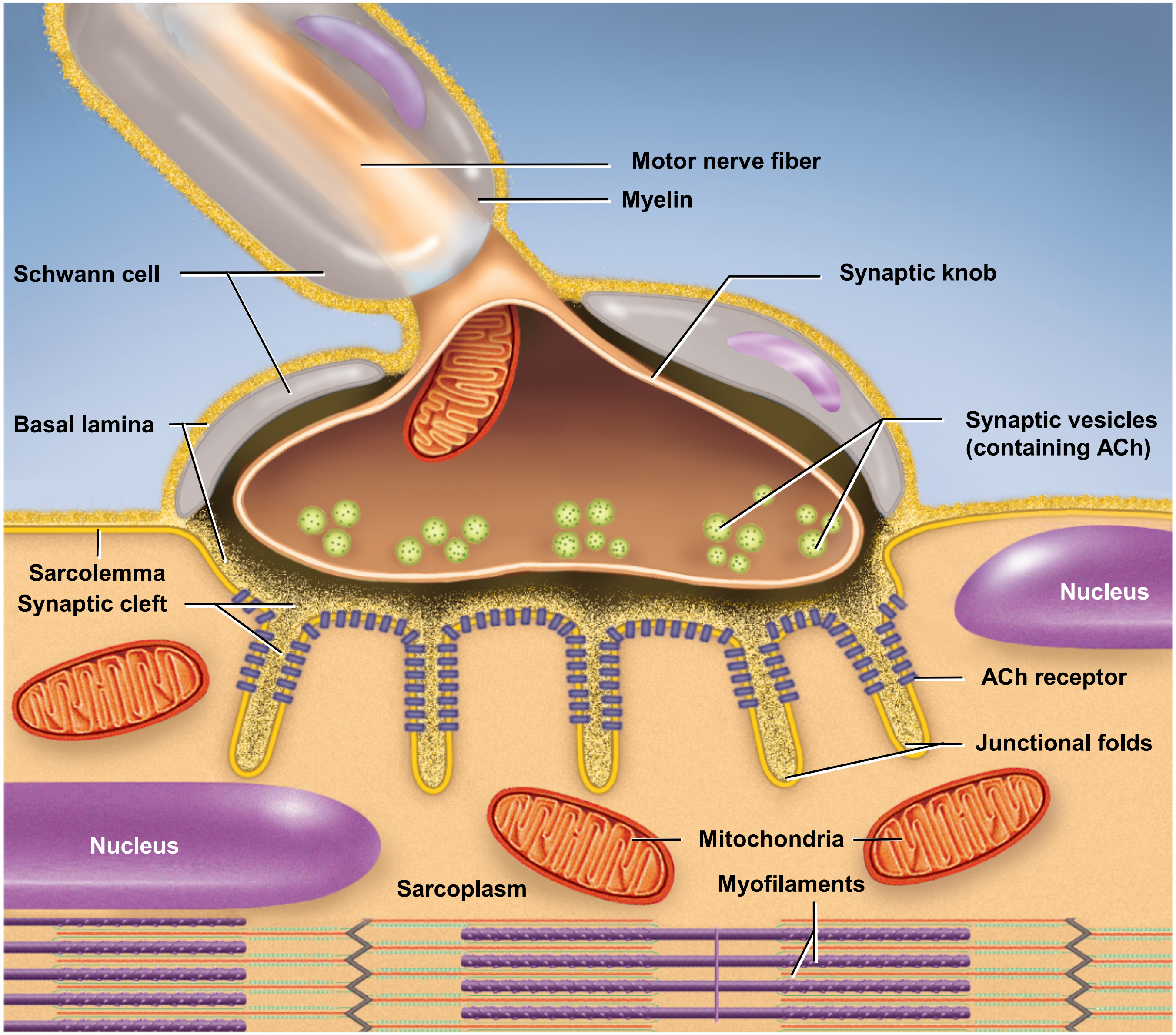


Figure 11.7b

Electrically Excitable Cells

- **muscle fibers** and **neurons** are electrically excitable cells
  - their plasma membrane exhibits voltage changes in response to stimulation

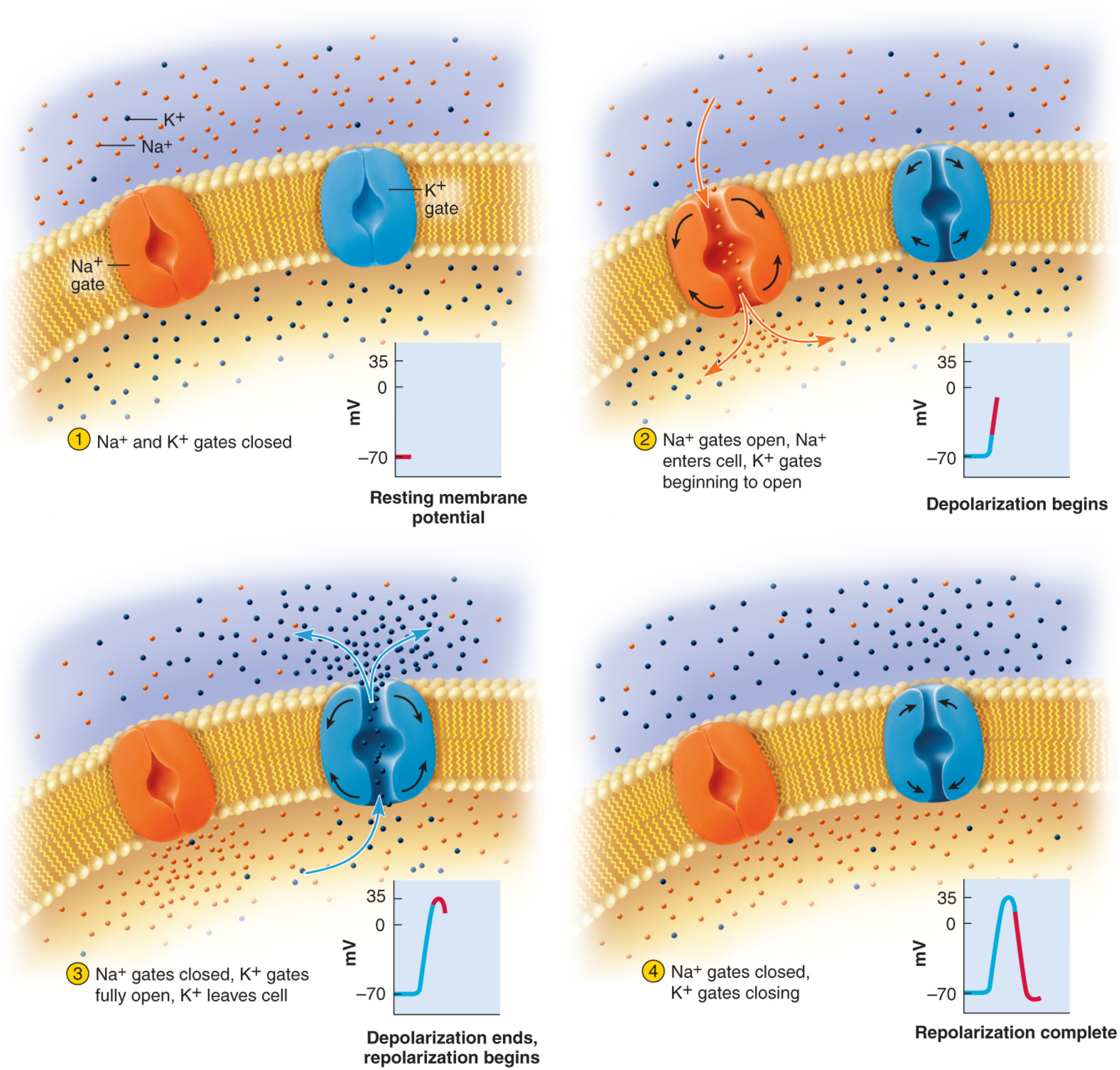
- in an **unstimulated (resting) cell**

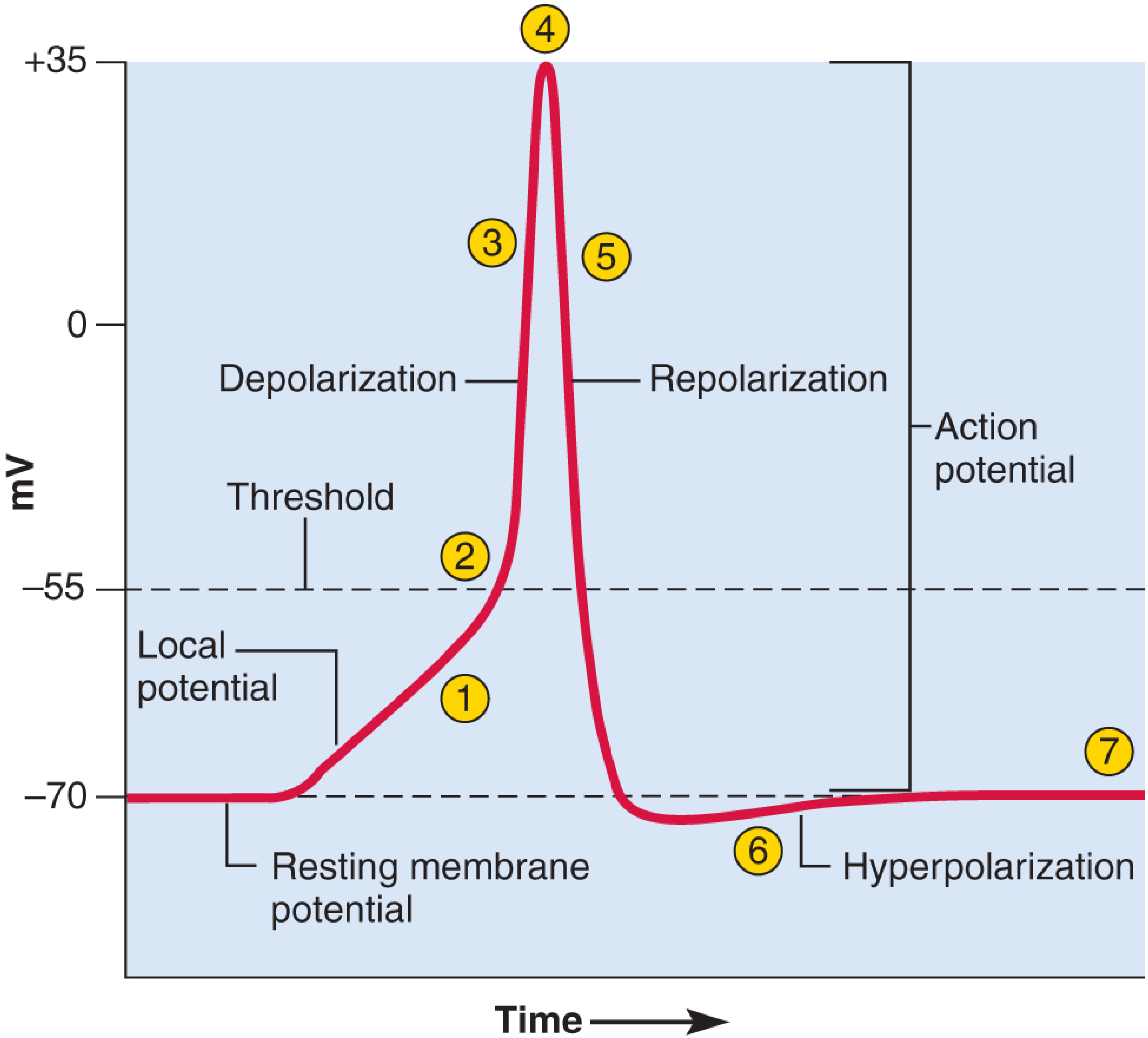
Out **Na+** K+ Anions-

In Na+ **K+** **Anions-**

- **voltage (electrical potential)** – a difference in electrical charge from one point to another

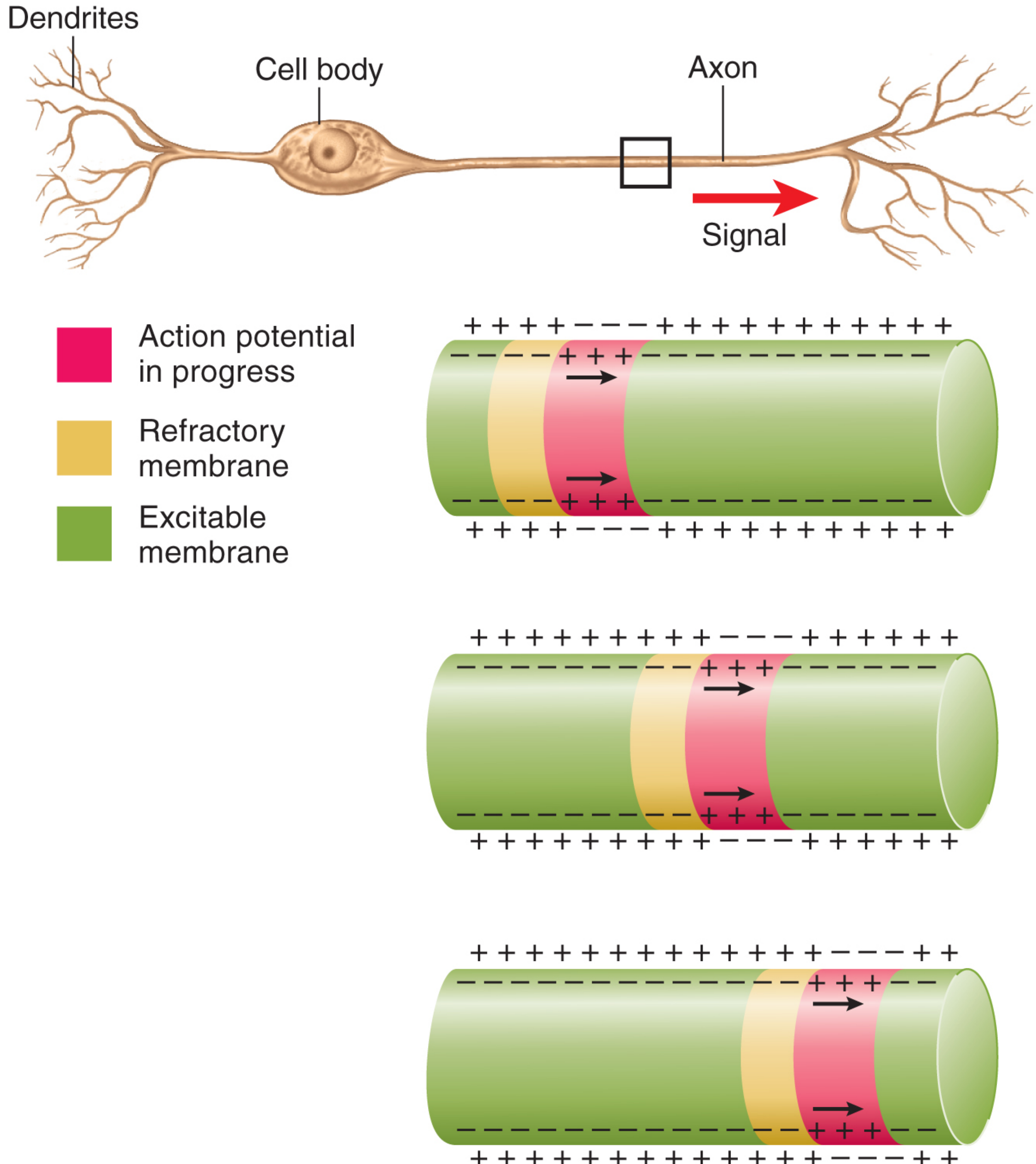
- **resting membrane potential** – about -90mV
  - maintained by sodium-potassium pump


K+
Na+
K+ gate
Na+ gate
1 Na+ and K+ gates closed
35
0
mV
–70
Resting membrane potential
2 Na+ gates open, Na+ enters cell, K+ gates beginning to open
35
0
mV
–70
Depolarization begins
3 Na+ gates closed, K+ gates fully open, K+ leaves cell
35
0
mV
–70
Depolarization ends, repolarization begins
4 Na+ gates closed, K+ gates closing
35
0
mV
–70
Repolarization complete



4
+35
3
5
0
Depolarization
Repolarization
Action potential
mV
Threshold
2
–55
Local potential
1
7
–70
Resting membrane potential
6
Hyperpolarization
Time

(a)


Dendrites
Cell body
Axon
Signal
Action potential in progress
Refractory membrane
Excitable membrane

Excitation of a Muscle Fiber

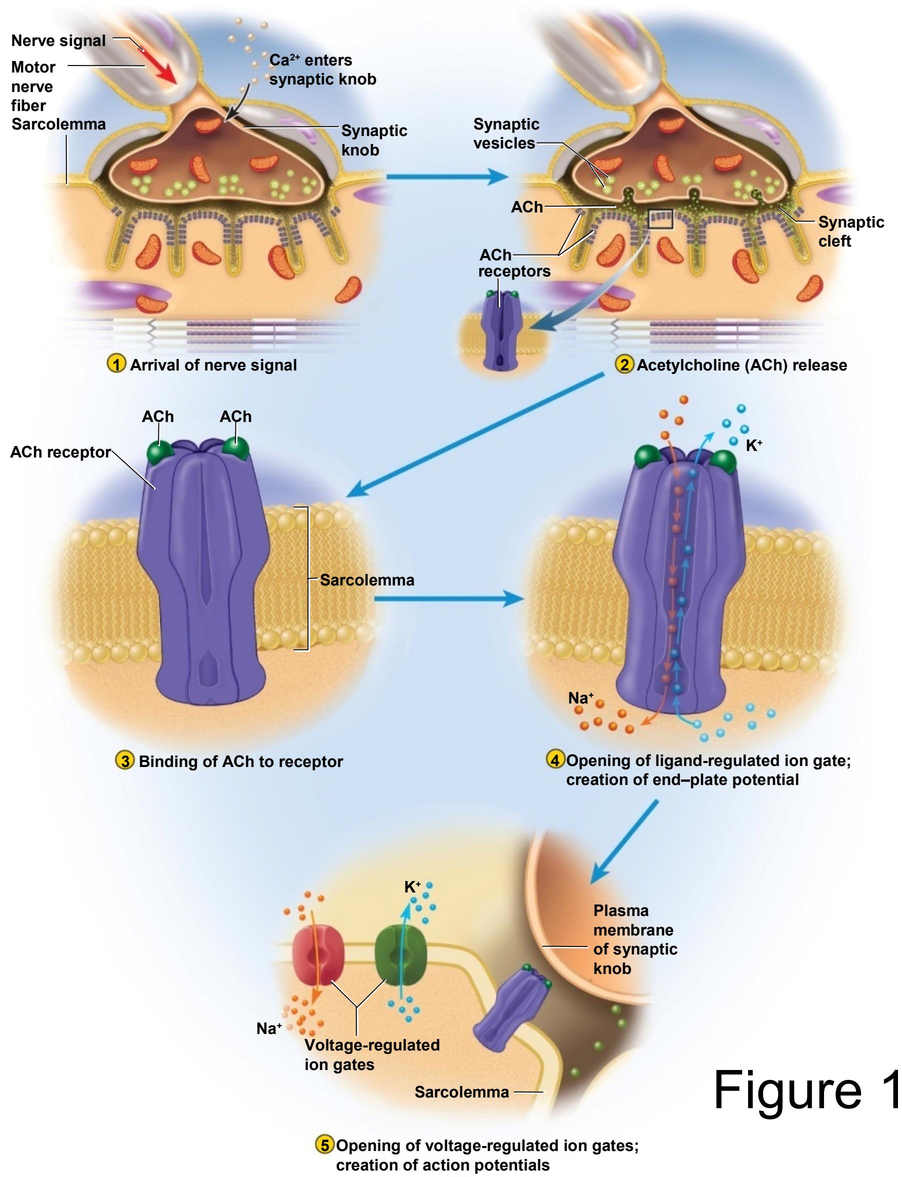


Figure 11.8

Excitation (steps 1 and 2)

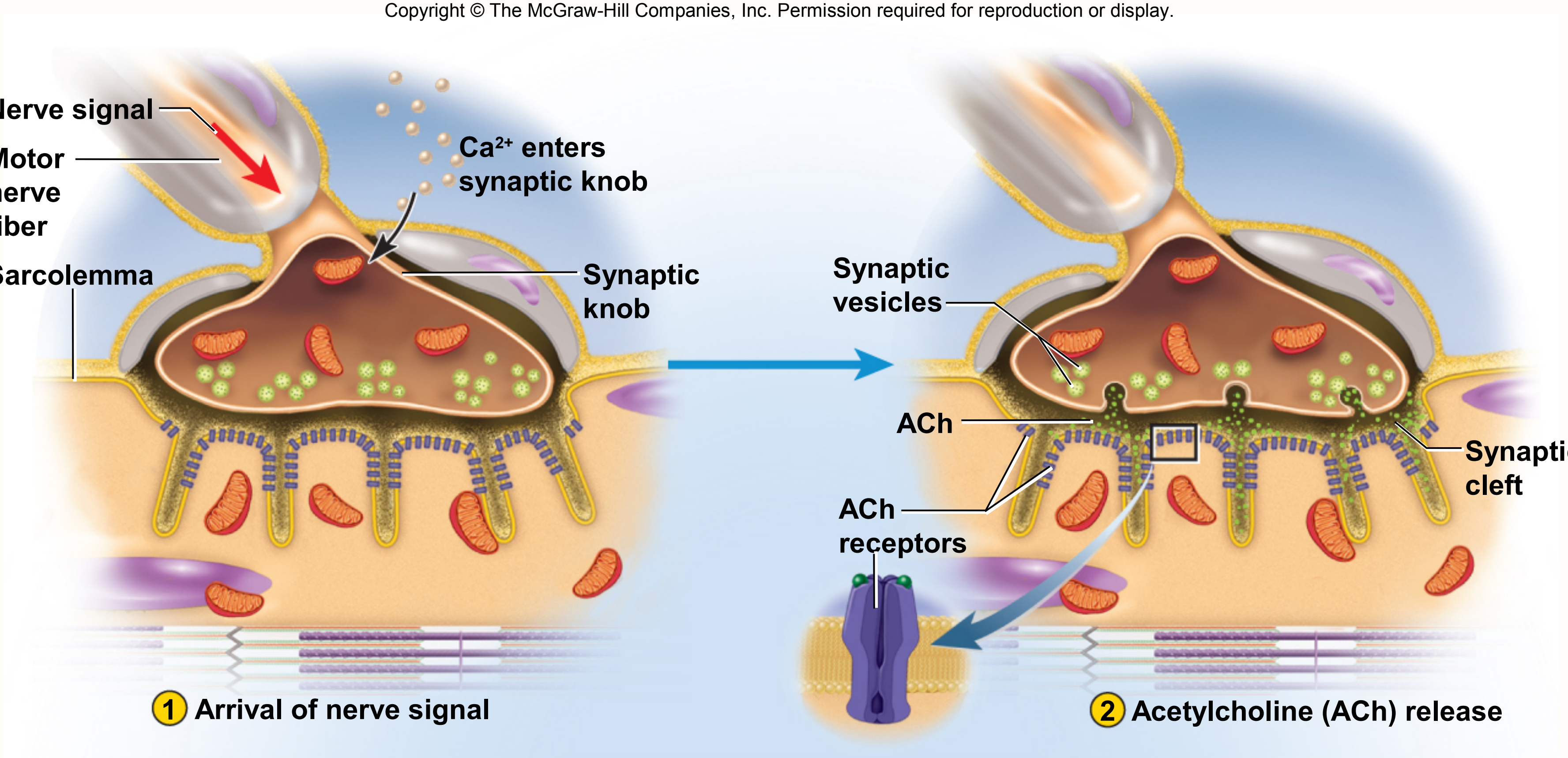
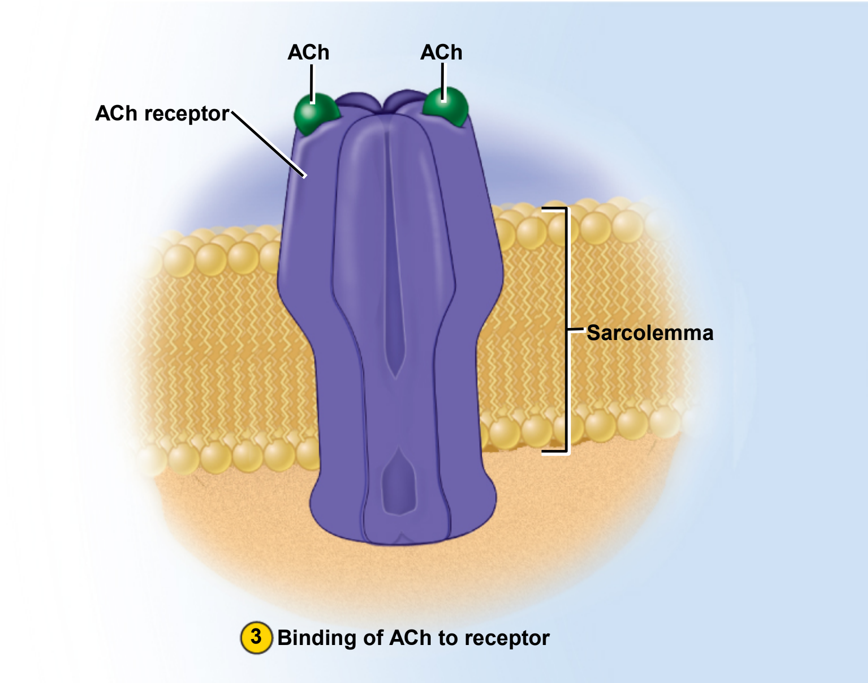


Figure 11.8 (1-2)

- nerve signal opens voltage-gated calcium channels in synaptic knob
- calcium stimulates exocytosis of ACh from synaptic vesicles
- ACh released into synaptic cleft

Excitation (steps 3 and 4)



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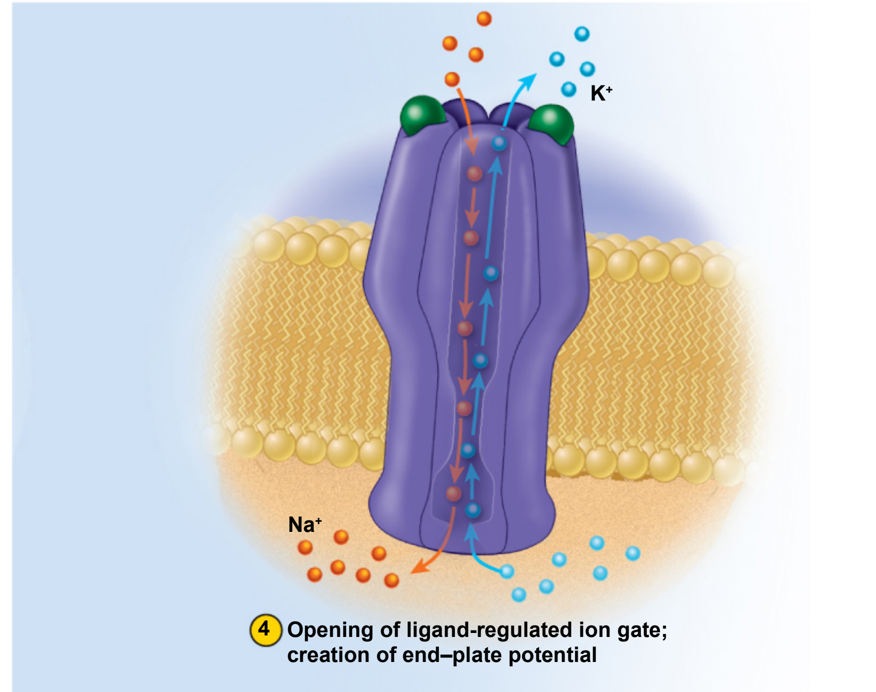


Figure 11.8 (3-4)

- two ACh molecules bind to each receptor protein, opening Na^+ and K^+ channels.
- Na^+ enters shifting RMP goes from -90mV to +75mV, then K^+ exits and RMP returns to -90mV - quick voltage shift is called an **end-plate potential (EPP).**

Excitation (step 5)

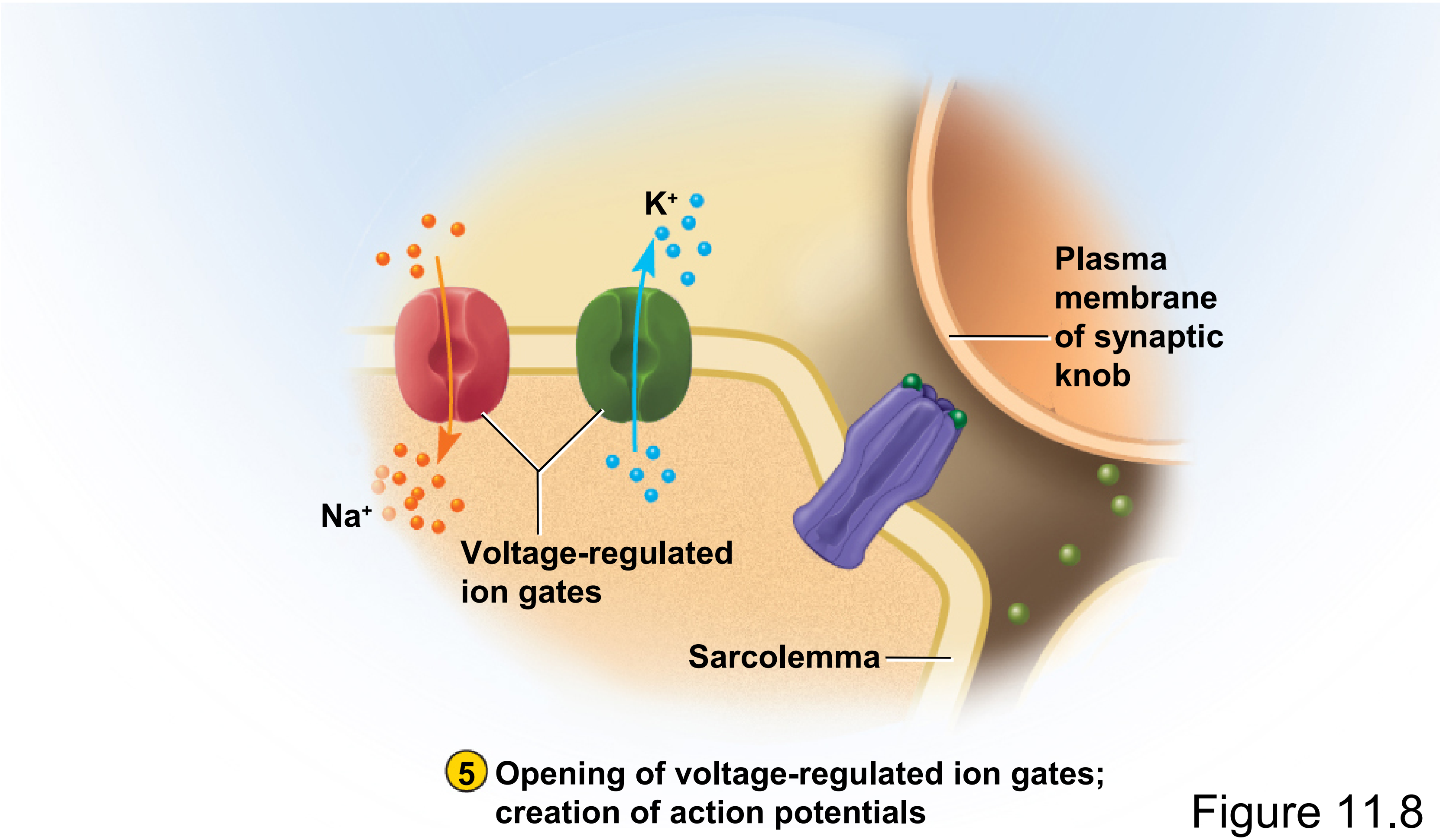


Figure 11.8 (5)

- voltage change (EPP) in end-plate region opens nearby voltage-gated channels producing an action potential that spreads over muscle surface.

Excitation-Contraction Coupling in Skeletal Muscle

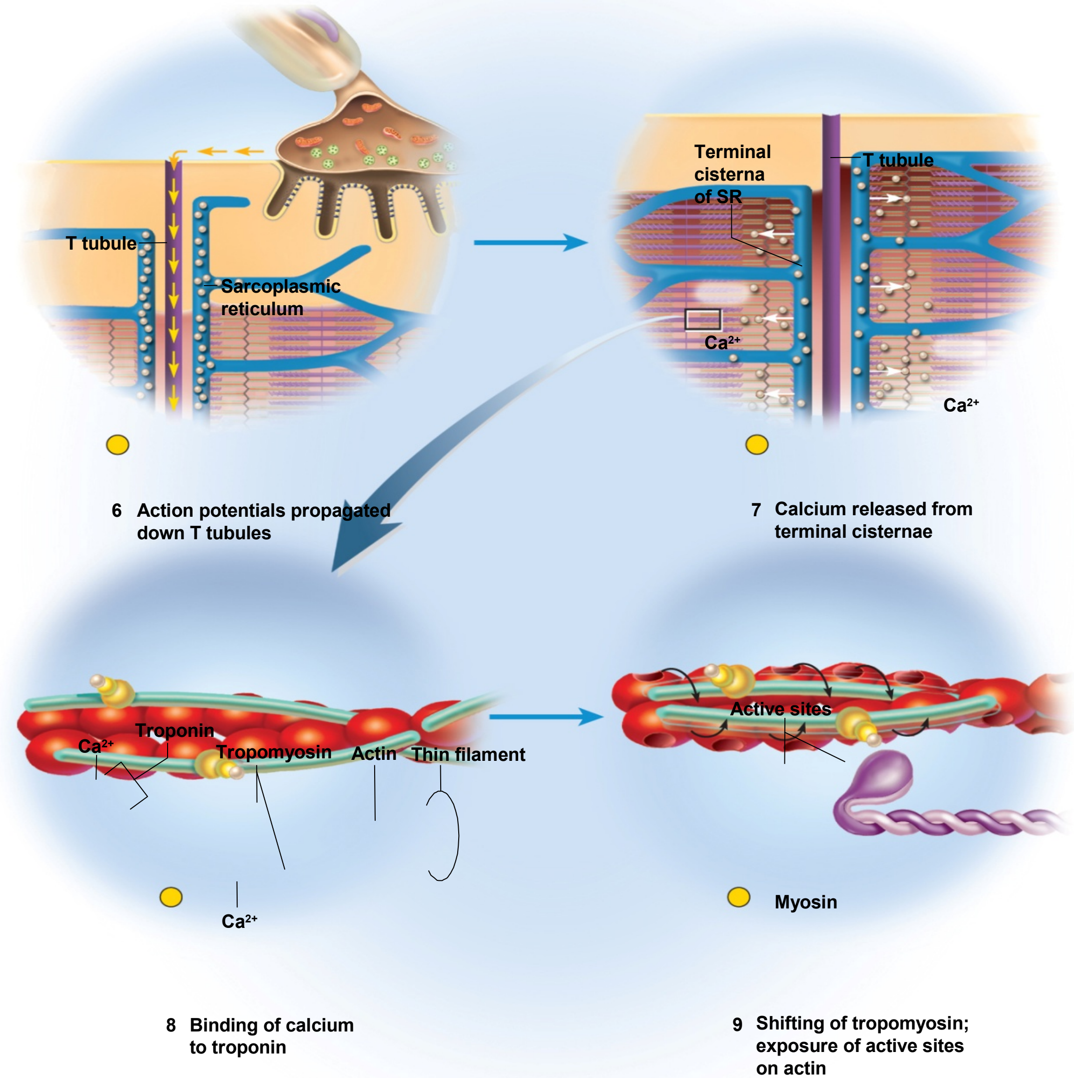


Figure 11.9 (6-9)

Excitation-Contraction Coupling (steps 6 and 7)

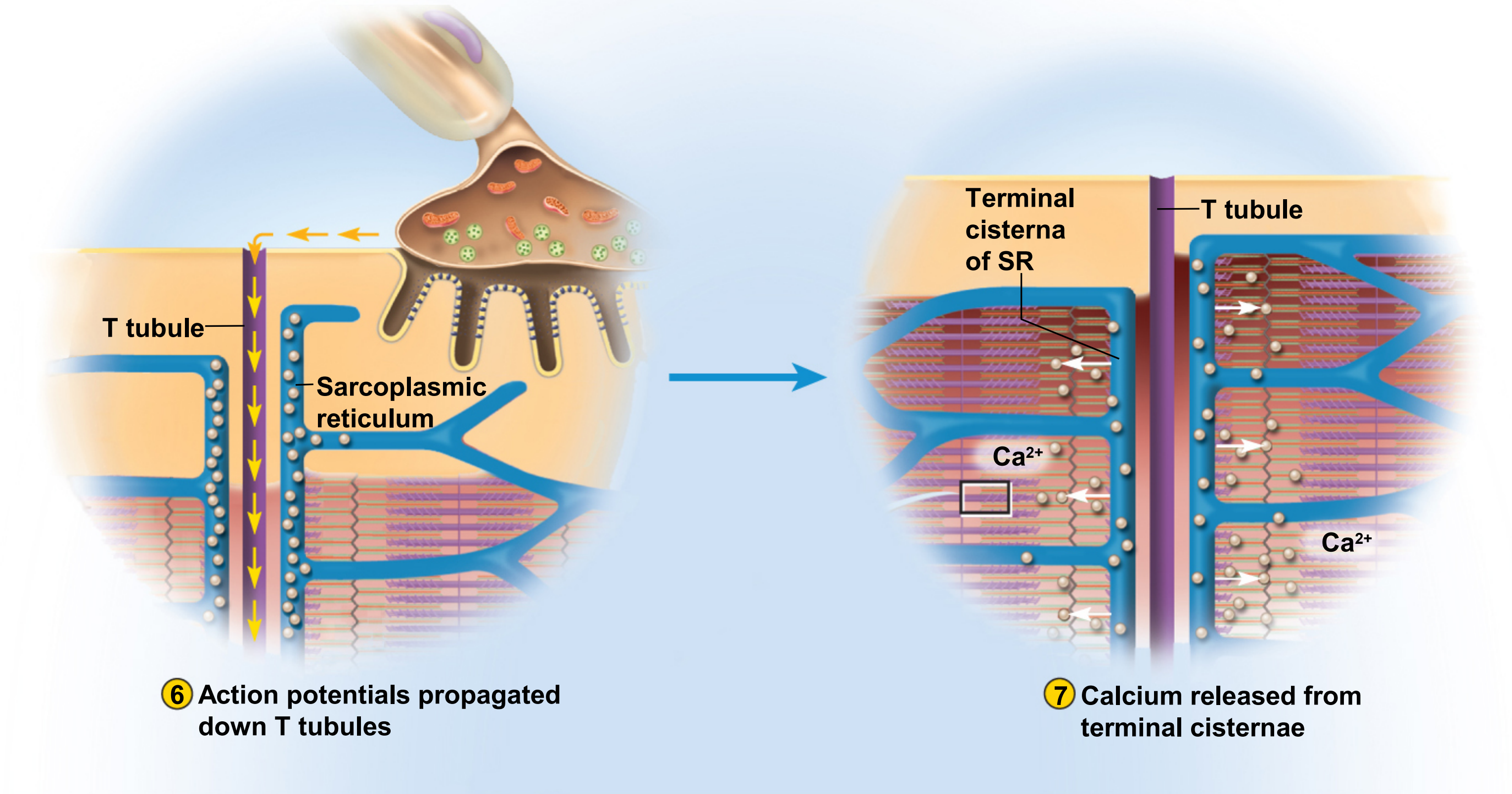


Figure 11.9 (6-7)

- action potential spreads down into T tubules
- opens voltage-gated ion channels in T tubules and Ca^{+2} channels in SR
- Ca^{+2} enters the cytosol

Excitation-Contraction Coupling (steps 8 and 9)

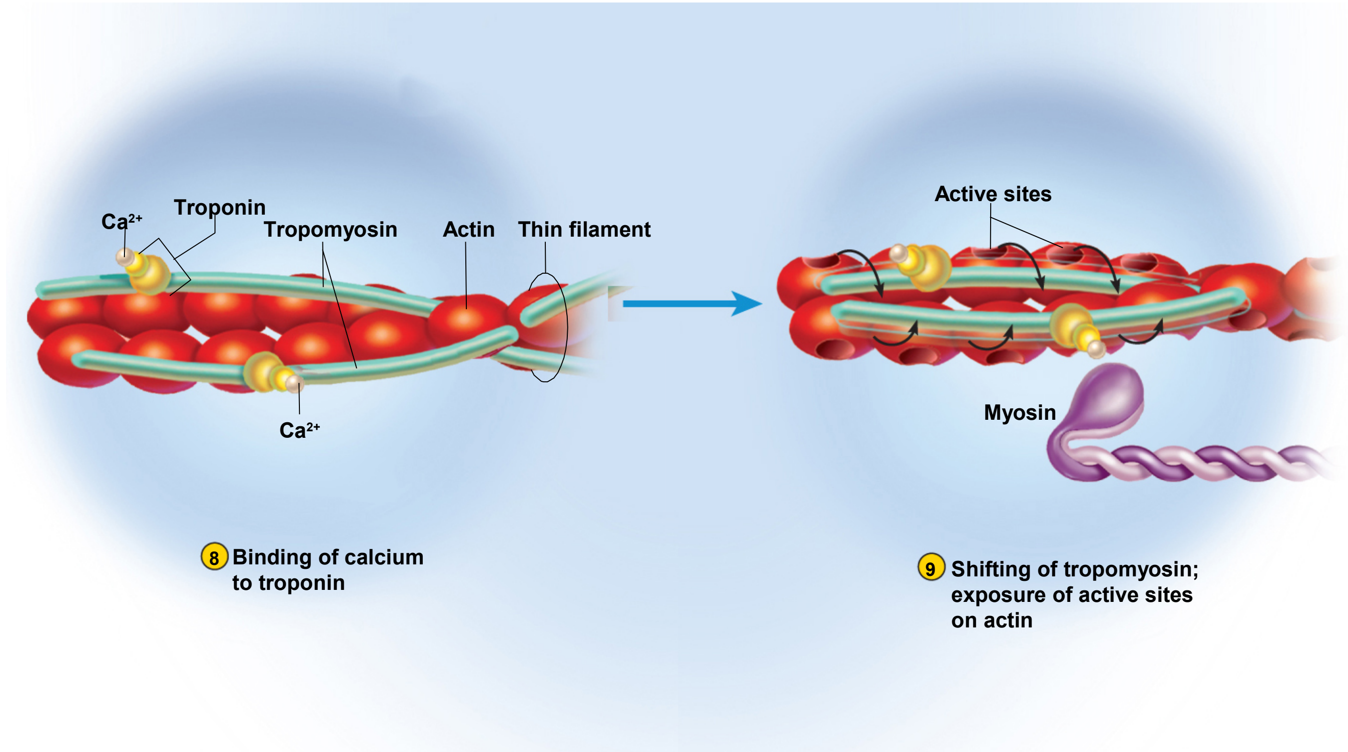
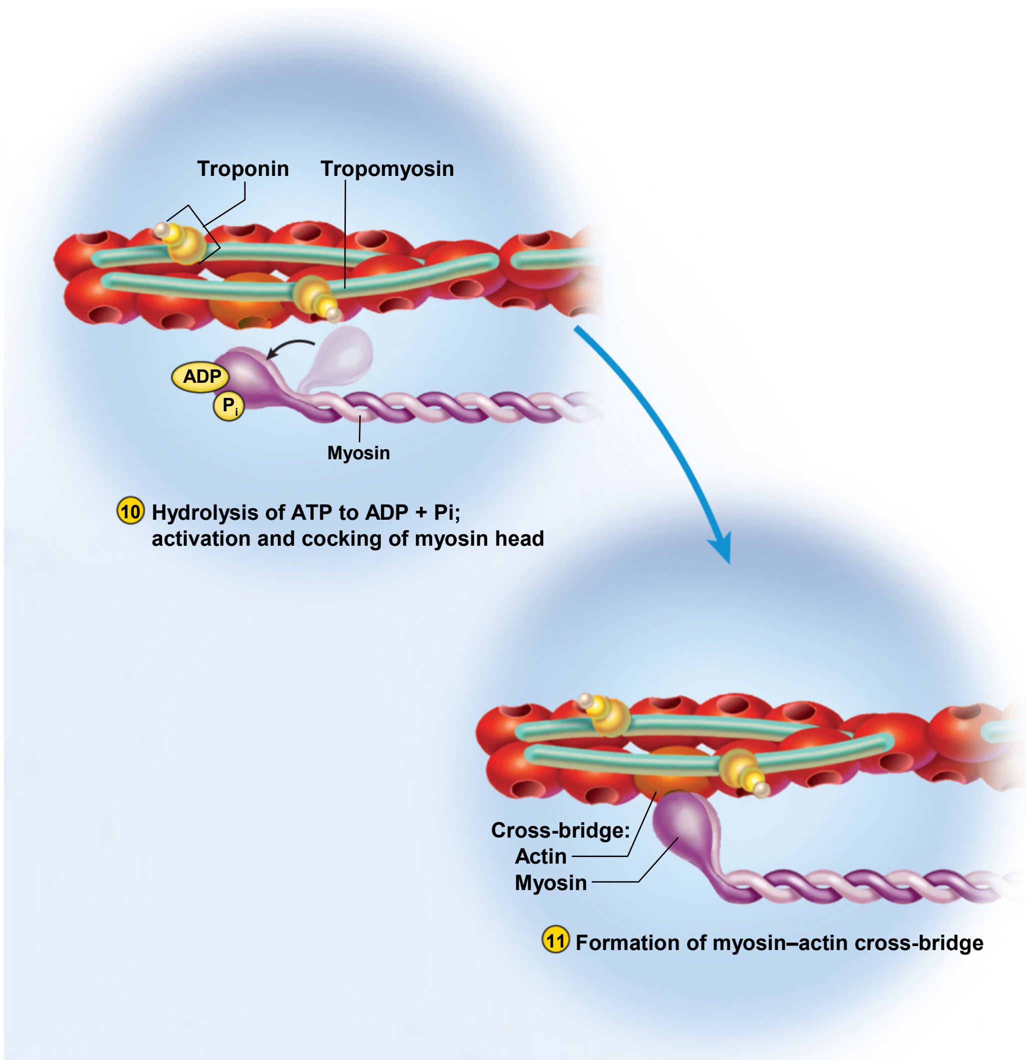


Figure 11.9 (8-9)

- calcium binds to troponin in thin filaments
- troponin-tropomyosin complex changes shape and exposes active sites on actin

Contraction (steps 10 and 11)



- myosin ATPase enzyme in myosin head hydrolyzes an ATP molecule
- activates the head "cocking" it in an extended position
  - ADP + P_i remain attached
- head binds to actin active site forming a myosin - actin cross-bridge

Figure 11.10 (10-11)

Contraction (steps 12 and 13)

- myosin head releases ADP and P_i, flexes pulling thin filament past thick - **power stroke**
- upon binding more ATP, myosin releases actin and process is repeated
  - each head performs 5 power strokes per second
  - each stroke utilizes one molecule of ATP

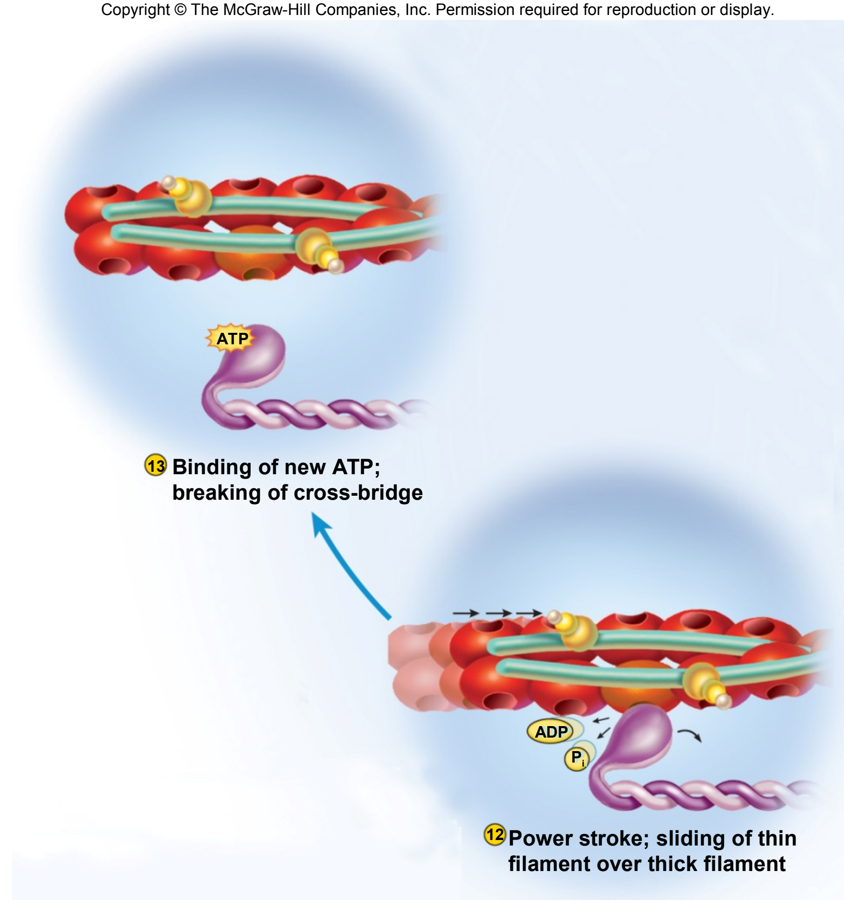


Figure 11.10 (12-13)

Relaxation (steps 14 and 15)

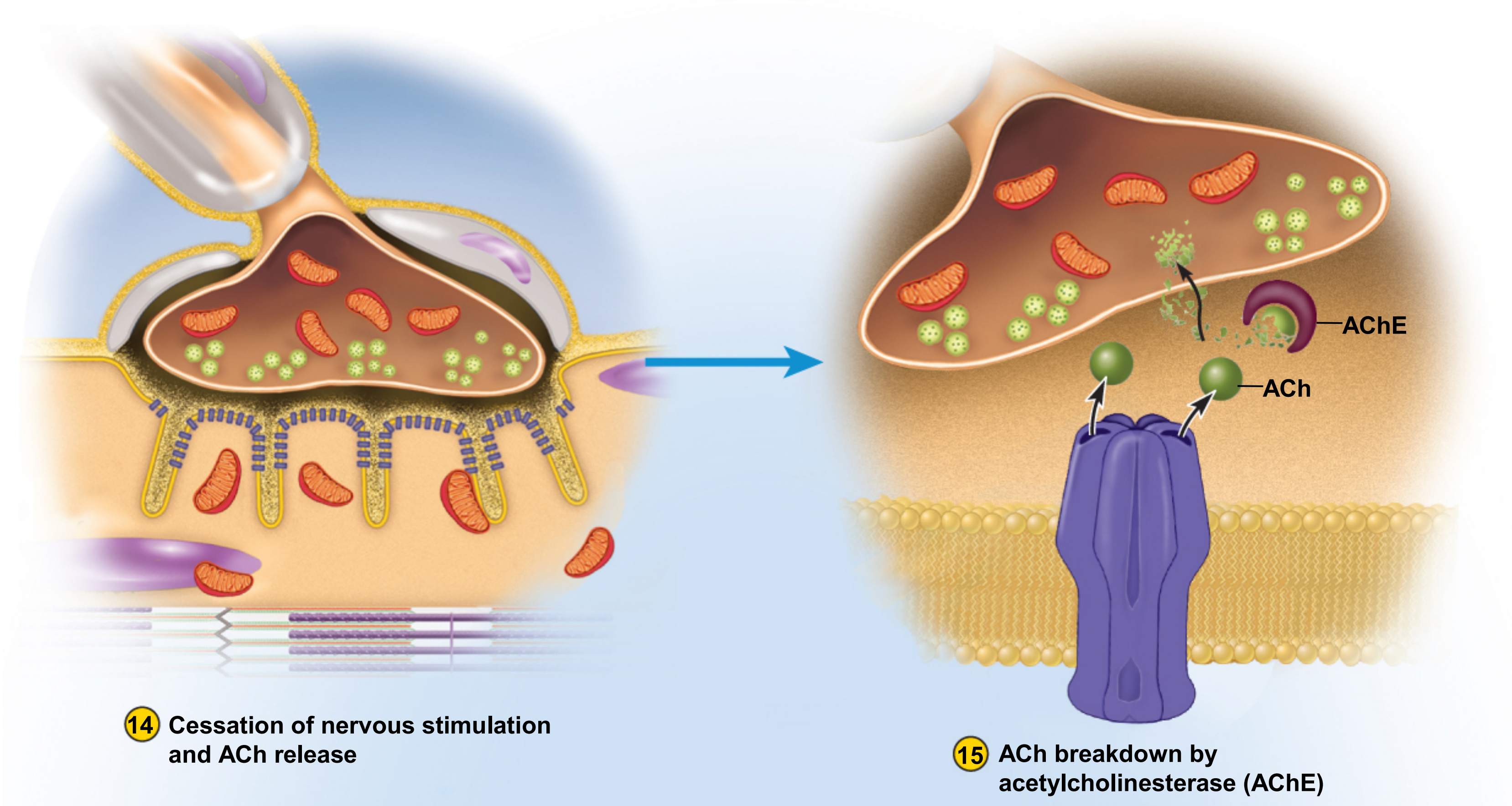
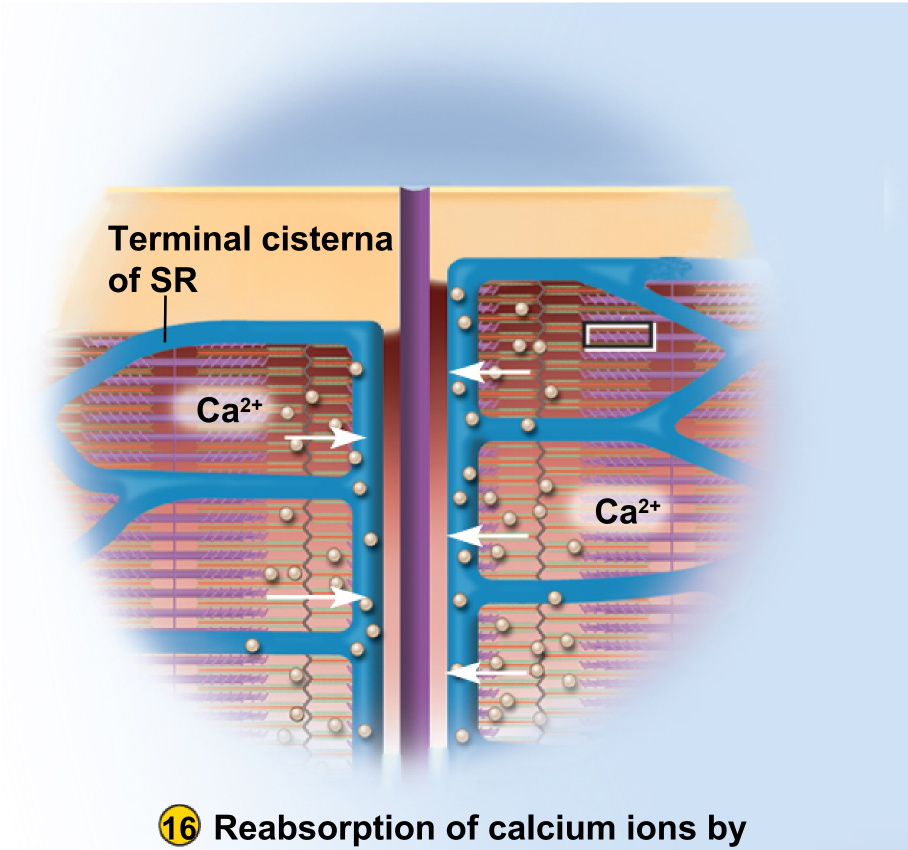


Figure 11.11 (14-15)

- nerve stimulation & ACh release stop
- AChE breaks down ACh & fragments reabsorbed into synaptic knob
- stimulation by ACh stops

Relaxation (step 16)



16 **Reabsorption of calcium ions by sarcoplasmic reticulum**

Figure 11.11 (16)

- Ca^{+2} pumped back into SR by active transport. Ca^{+2} binds to calsequestrin while in storage in SR
- ATP is needed for muscle relaxation as well as muscle contraction.

Relaxation (steps 17 and 18)

- Ca^{+2} removed from troponin is pumped back into SR
- tropomyosin reblocks the active sites
- muscle fiber ceases to produce or maintain tension
- muscle fiber returns to its resting length
  - due to recoil of elastic components & contraction of antagonistic muscles

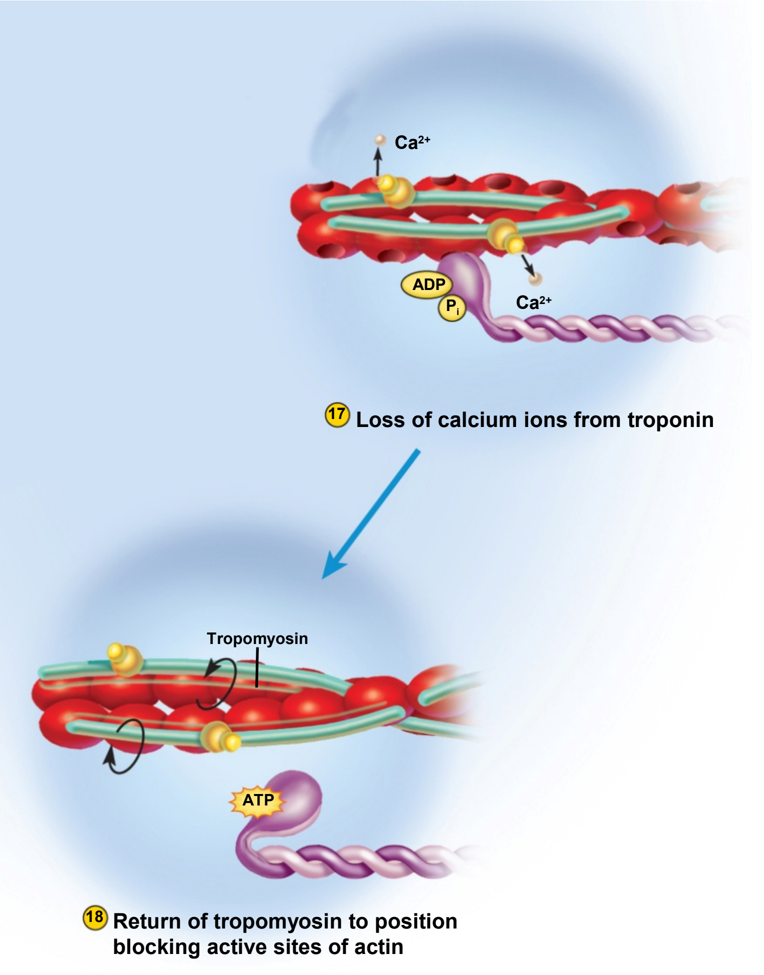


Figure 11.11 (17-18)

Muscle Metabolism

- all muscle contraction depends on **ATP**
- ATP supply depends on availability of:
  - **oxygen**
  - **organic energy sources** such as glucose and fatty acids
- two main pathways of ATP synthesis
  - **anaerobic fermentation**
    - enables cells to produce ATP in the absence of oxygen
    - yields little ATP and toxic lactic acid, a major factor in muscle fatigue
  - **aerobic respiration**
    - produces far more ATP
    - less toxic end products (CO_2 and water)
    - requires a continual supply of oxygen

Modes of ATP Synthesis During Exercise

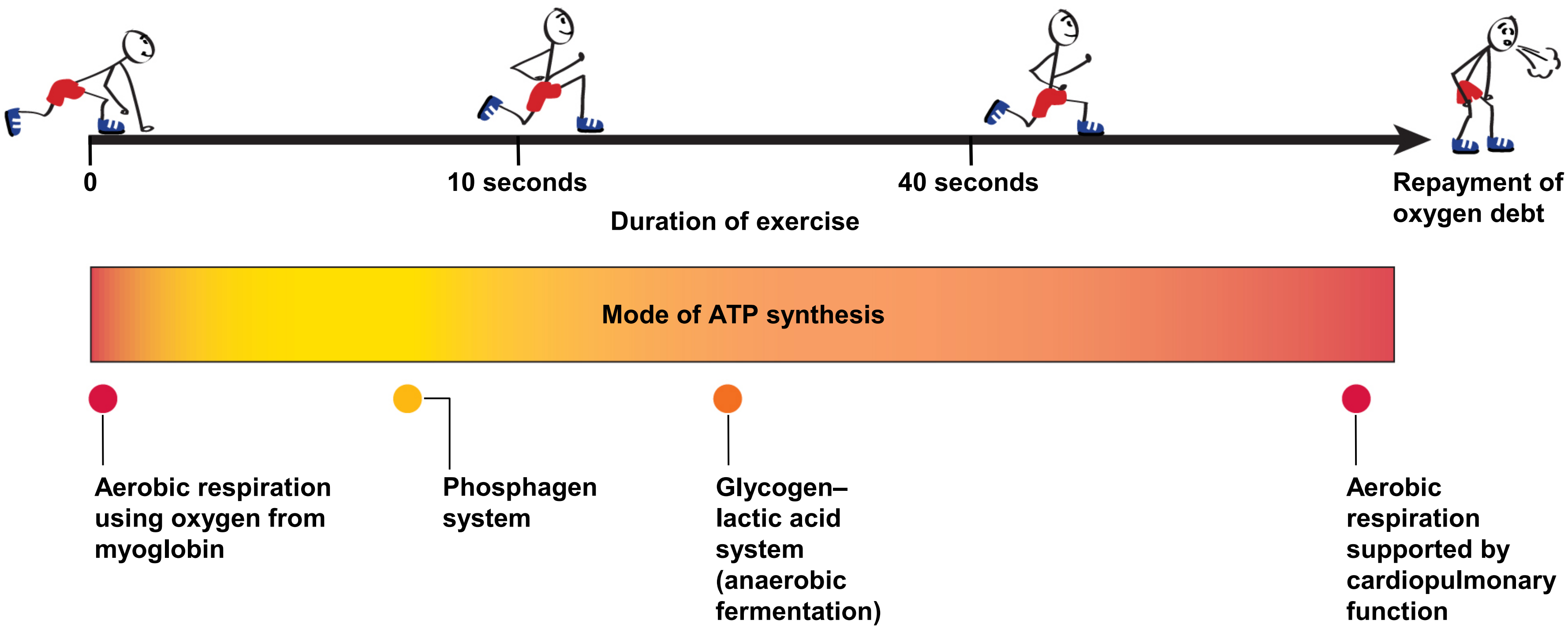


Figure 11.18

Immediate Energy Needs

- short, intense exercise (100 m dash)
  - oxygen need is briefly supplied by **myoglobin** for a limited amount of aerobic respiration at onset – rapidly depleted
  - muscles meet most of ATP demand by borrowing phosphate groups (P_i) from other molecules and transferring them to ADP
- two enzyme systems control these **phosphate transfers**
  - **myokinase** – transfers P_i from one ADP to another converting the latter to ATP
  - **creatine kinase** – obtains P_i from a phosphate-storage molecule creatine phosphate (CP)
    - fast-acting system that helps maintain the ATP level while other ATP-generating mechanisms are being activated
- **phosphagen system** – ATP and CP collectively
  - provides nearly all energy used for short bursts of intense activity

Immediate Energy Needs

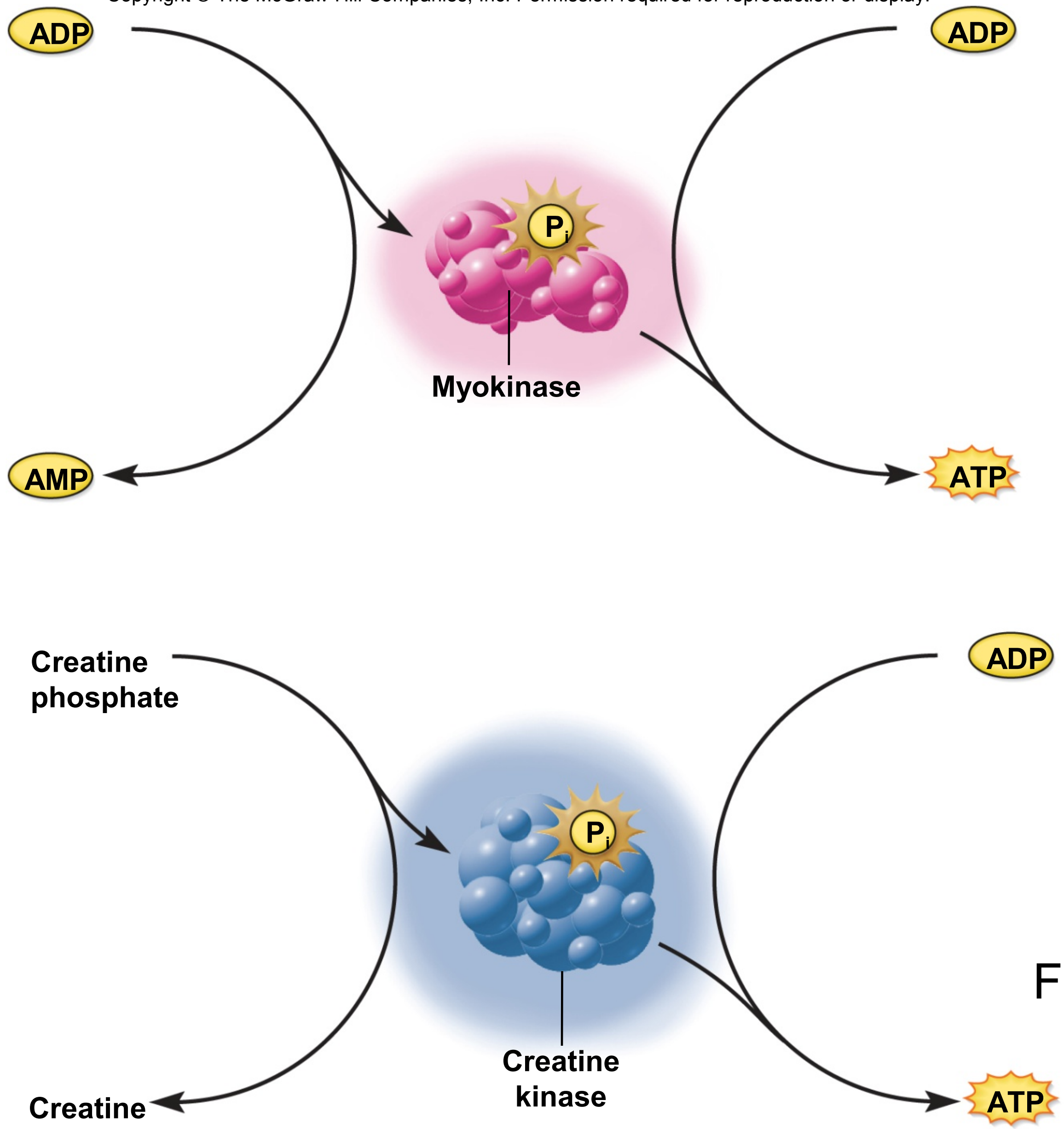


Figure 11.19

Short-Term Energy Needs

- as the phosphagen system is exhausted
- muscles shift to **anaerobic fermentation**
  - muscles obtain glucose from blood and their own stored glycogen
  - in the absence of oxygen, **glycolysis** can generate a net gain **of 2 ATP** for every glucose molecule consumed
  - converts glucose to lactic acid
- produces enough ATP for **30 – 40 seconds** of maximum activity

Long-Term Energy Needs

- after 40 seconds or so, the respiratory and cardiovascular systems “catch up” and deliver oxygen to the muscles fast enough for aerobic respiration to meet most of the ATP demands
- aerobic respiration produces 36 ATP per glucose
  - efficient means of meeting the ATP demands of prolonged exercise
  - one’s rate of **oxygen consumption** rises for 3 to 4 minutes and levels off to a steady state in which aerobic ATP production keeps pace with demand

Smooth Muscle

- **fusiform shape**
- Ca^{2+} comes from the ECF
- some smooth muscles lack nerve supply, while others receive autonomic fibers, not somatic motor fibers as in skeletal muscle
  - smooth muscle is **involuntary** and can contract without nervous stimulation
    - can contract in response to chemical stimuli
      - hormones, carbon dioxide, low pH, and oxygen deficiency
    - in response to stretch
- slow in comparison to skeletal muscle
  - Ca^{+2} binds to calmodulin instead of troponin
- **latch-bridge mechanism** is resistant to fatigue
  - heads of myosin molecules do not detach from actin immediately
  - maintains tetanus tonic contraction (smooth muscle tone)
    - arteries – vasomotor tone   intestinal tone

Layers of Visceral Muscle

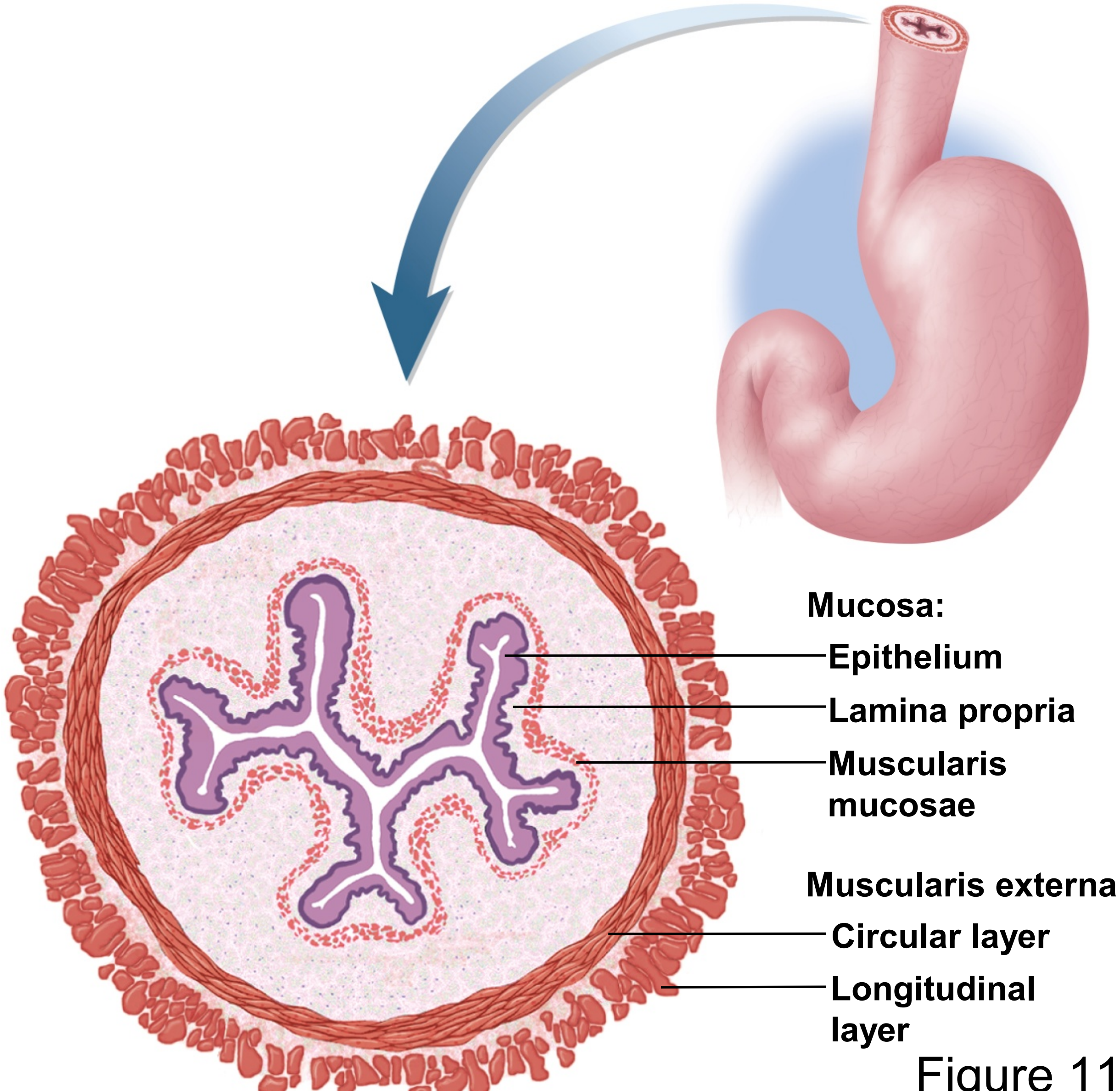
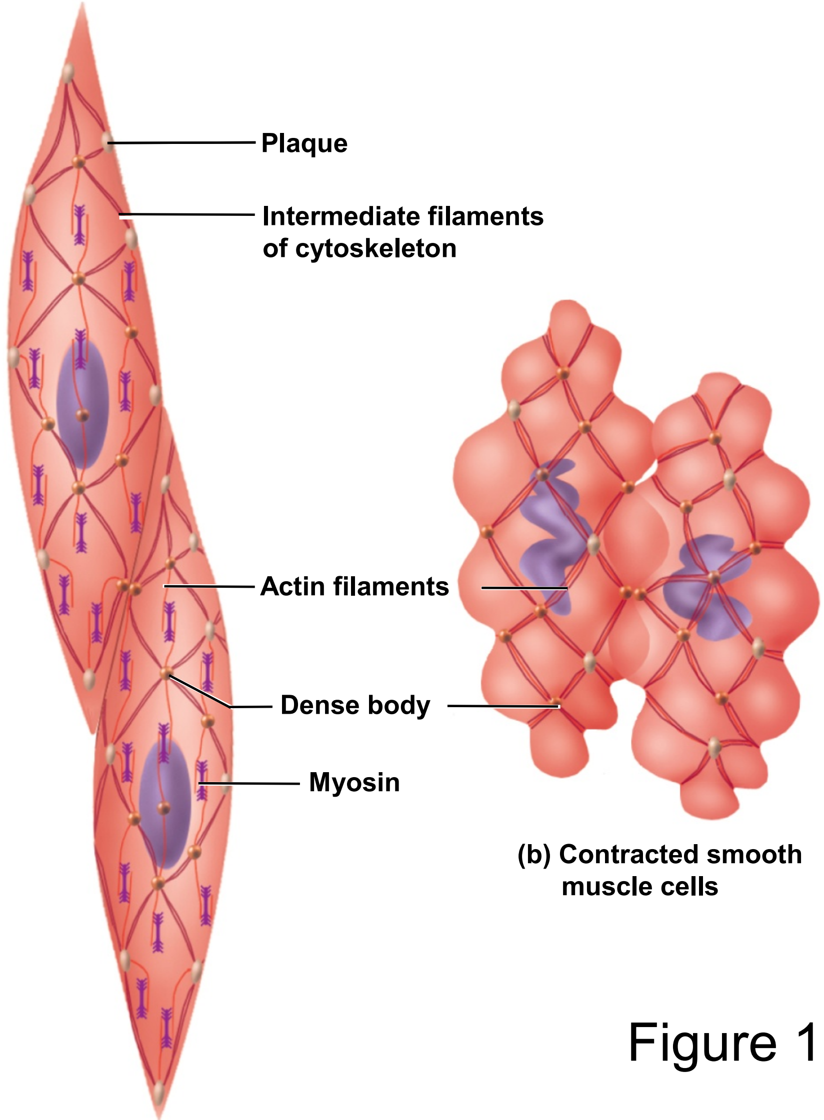


Figure 11.22

Contraction of Smooth Muscle



(a) Relaxed smooth muscle cells

(b) Contracted smooth muscle cells

Figure 11.24