Objectives:
- Be able to concisely describe the gross anatomy of the spinal cord.
- Be able to describe the structure, organization, and basic function of the cord in cross-section.
- Be able to explain the distinct anatomy and function of the dorsal and ventral roots.
- Be able to describe what information enters and leaves the spinal cord.
- Be able to explain the basic organization of the stretch and withdrawal reflexes.
- Be able to describe what a central pattern generator is.
- Be able to describe how spinal functions can be regulated by, and interact with, descending pathways.

I. Overview
The spinal cord is the long bundle of nerves and neurons that runs down the middle of the back. It is enclosed in the vertebral column (spine) and is considered part of the central nervous system. The spinal cord is a complicated processor of sensory and motor information. It regulates sensory inflow and contributes to the control of movements. In short, the spinal cord looks and often functions like a cable bringing sensory information from the body to the brain and sending movement commands from the brain to the body. In addition, the spinal cord also processes sensory and motor signals.

Note: For everything discussed in sections III - VI below, there are analogous structures and functions for the head and face that are mediated by cranial nuclei and other brainstem neurons.

II. Spinal Cord Anatomy
A. Gross anatomy
1. The spinal cord sits in the vertebral canal inside the vertebral column (See Figure 1).
2. The spinal cord is symmetric about the midline and labeled for associated vertebrae. There are five groups of vertebrae: Cervical (C), Thoracic (T), Lumbar (L), Sacral (S) and Coccygeal (Co). (See Figures 2 and 3)
3. There are 31 pairs of afferent and efferent spinal nerves that branch outside the vertebral column to form peripheral nerves.

Figure 1: The spinal cord rests in the spinal canal inside the vertebral column. Spinal nerves extend outward from the cord joining the CNS and PNS.
3. Each level of the cord receives somatic sensory information from, and sends somatic motor commands to, a specific part of the body. In addition, the T1-L2 segments include sympathetic neurons and the S1-S5 segments contain parasympathetic neurons. See figure 4.

4. Because the spinal cord stops growing earlier in development than the rest of the body, the cord is shorter than the vertebral column; it ends at ~L1 in adults, below which the vertebral canal contains only dorsal and ventral roots.

5. Dorsal and ventral roots join after the dorsal root ganglion to form spinal nerves that exit the vertebral column at the associated vertebral level; below the cervical segments the nerve roots travel more and more caudally to reach their exit points.

Figure 2. Spinal sectional anatomy

Figure 3. Cross section of 4 different spinal cord segments.
Figure 4: The labeled dermatomes show the corresponding spinal cord sections that receive input from receptors in the skin and to which motor commands are sent.

B. Cross Sectional Anatomy

1. Spinal gray matter (composed of cell bodies) is arranged in an “H” pattern inside white matter (composed of axons). This “H” is functionally arranged in the sensory-dorsal, motor-ventral organization that is fairly consistent throughout the brainstem. The 'crossbar' of the “H” or intermediate section of gray matter is filled, mainly, with interneurons. See figures 5 and 6.

2. Somatosensory information enters the cord through primary afferent axons in dorsal roots; cell bodies of these neurons are in the dorsal root ganglia; branches of these axons synapse in the ipsilateral dorsal horns (the top arms of the “H”).

3. Axons of motoneurons leave the cord through ventral roots to contract ipsilateral muscles. Motoneuron cell bodies are in the ventral horns (the bottom arms of the “H”), motoneurons for axial muscles are in the medial ventral horn, and motoneurons for distal muscles are in the lateral ventral horn.

4. Cord cross section looks different at different segments. See Figure 3.
   a. Cervical and lumbar segments are enlarged because they contain sensory neurons, motoneurons and interneurons related to the arms and legs, respectively.
   b. There is a rostral-to-caudal decrease in the amount of white matter because each level of the cord contains the fibers ascending from, and descending to, all segments more caudal.
III. Physiology of the Spinal Cord

A. Somatosensory inputs to the dorsal horn

1. Primary afferent axons in the dorsal roots originate from different types of somatosensory receptors in the periphery – touch (cutaneous or tactile), pain (nociception), temperature, and proprioception (e.g., muscle spindles, Golgi tendon organs). Dorsal roots also carry afferent axons from viscera.

2. Modality, intensity and location of somatosensory stimuli are established by the peripheral receptors.

3. Ascending signals travel through columns of fibers that delineate both the modality and destination of the information. (Figure 7)

4. Almost all signals from the peripheral nervous system synapse in the ipsilateral dorsal horn; where they go from there depends on what type of information is being conveyed. (Figure 8)
a. Pain and temperature signals cross the midline through the anterior commissure and are carried to the thalamus via the lateral spinothalamic tract.

b. Crude touch and pressure signals are carried through the anterior spinothalamic tracts. Approximately half of the fibers cross the midline through the anterior commissure before ascending to the thalamus.

c. Fine touch, pressure and position signals are relayed via either the fasiculus cuneatus or fasiculus gracilis. The latter conveys information from the lower limbs, the former from the upper limbs. Signals travel ipsilaterally until they reach the nuclei gracilis and cuneatus where they synapse. The secondary axons then cross the midline in the internal arcuate fibers.

d. Information about muscle tone is conveyed ipsilaterally through the spinocerebellar tract.

B. Motor signals synapse in the ventral horns

1. Descending axons originate from different places in the brain and also carry different types of information. As above, they tend to be grouped into columns, though the boundaries are much more ill-defined. (Figures 7, 8)

a. The lateral and anterior corticospinal tracts carry signals for muscle movement. They carry information from motor cortex to secondary motor neurons in the ventral horn, either directly or via interneurons.

b. The rubrospinal tract overlaps almost entirely with the lateral corticospinal tract. Originating in the red nucleus, it seems to carry information for voluntary movement very like that of the lateral corticospinal tract. Only fine-finger movement signals are absent.

c. The reticulospinal tract carries signals from the reticular formation of the pons to flexor and extensor muscles.

d. The vestibulospinal tract carries vestibular information from the vestibular nuclei in the medulla. These signals help to maintain upright posture.

e. The intermediolateral cell column is an extended ganglion of sympathetic neurons. Signals arrive from the thalamus, synapse with cells within it, and those then send commands via the cells of the sympathetic ganglion.

Figure 7: Ascending and Descending tracts
Figure 8: Physiology of sensory and motor connections within the spinal cord.

**Modalities**
- Pain
- Temperature

**Modalities**
- Crude Touch
- Pressure

**Fine Touch**
- Pressure
- Position / Joint

**Muscle Tone**

**Interomediolateral Cell Column**
- (Only in Thoracic Cord)

**Sympathetic Ganglion**

**Hypothalamus**
IV. Spinal Reflexes
   A. Activation of primary somatosensory afferents elicits stereotyped behaviors known as spinal reflexes, which can be mediated entirely by spinal pathways.
   B. Stretch (or monosynaptic or deep tendon) reflex resists changes in muscle length, usually at a single joint. (See figure 9)
      1. Stretch activates group Ia muscle spindle afferents that monosynaptically excite motoneurons of the same and synergistic muscles.
      2. Reciprocal inhibition of antagonist muscles is mediated by an interposed inhibitory interneuron.
   C. Flexion (or withdrawal) and cross-extension reflexes withdraw a limb from noxious stimuli and provide postural support with the opposite limb.
      1. Polysynaptic pathways excite flexor and inhibit extensor muscles on the side ipsilateral to the stimulus and excite extensor and inhibit flexor muscles on the contralateral side.
      2. Reflex involves neurons in multiple segments controlling multiple joints.

Figure 9: Spinal Reflexes
V. Spinal Cord Pattern Generators
   A. Rhythmic patterns of muscle activity, underlying movements such as locomotion and chewing, can be produced by groups of interconnected neurons, termed a central pattern generator (CPG), independent of sensory or descending inputs.
   B. CPG function can be modulated by somatosensory inputs, as for locomotor adjustments to obstacles or different surfaces, and by descending pathways, as for changing locomotor speed.
   C. Extensors and flexors will fire in an alternating pattern during locomotion. It is possible to witness firing of muscles involved in rhythmic movement even when descending input has been obliterated. This is because the activity is controlled by circuits of neurons, called central pattern generators, located within the spinal cord itself. (Figure 10)
   D. One idea for how CPGs work involves reciprocally-coupled 'half center oscillators'. Often, during rhythmic movement, when one group of cells fires, another is dormant; and then the roles are reversed. A popular suggestion for how this might be accomplished is that the cells inhibit their counterparts at the same time that they themselves are active. Further they inhibit any inhibition they themselves could be receiving at that time. Then, as their firing ceases, both forms of inhibition are released. The events would cycle repeatedly; yielding rhythmic activation of muscles. (Figure 11)

V1. Descending Control of Spinal Circuits
   A. Brainstem and cerebral cortical signals converge on the same spinal neurons that mediate sensory transmission and execute reflexes and rhythmic movements.
      1. This convergence allows for descending modulation of reflex movements, CPG function, and ascending sensory transmission.
      2. This convergence also allows somatosensory information entering the spinal cord to modulate descending commands for movement.

Figure 10: Severed cord does not impair CPG-guided locomotion in cats
Central Pattern Generator Circuit Models (Vertebrate and Lamprey)