Nervous System Evolution, Sensation and Behavior in Invertebrates

- Evolution of the central nervous system
- Sensory perception
- Behavior
Trends in Nervous System Evolution

• Nerve nets
• Paired nerve cords (3-4 pairs)
• Reduction in number of nerve cords
• Dominance of ventral pair of nerve cords
• Increasing size of cerebral ganglia and formation of a “brain”
• Dorsal nerve cord of chordates
Nervous systems show diverse patterns of organization

- **Nerve nets** (Cnidaria, Ctenophora, Echinodermata)
Platyhelminthes (flatworm)  
Nervous systems

From multiple pairs of nerve cords to a single pair located ventrally
• The insect nervous system consists of a pair of ventral nerve cords with several segmental ganglia.
  – The two chords meet in the head, where the ganglia from several anterior segments are fused into a cerebral ganglion (brain).
  – This structure is close to the antennae, eyes, and other sense organs concentrated on the head.
Cephalization - concentration of sensory apparatus and nervous system anteriorly)
Nervous System in Sea Squirts

Phylum Chordata – Subphylum Urochordata – Class Asciidiacea
Sensory receptors transduce stimulus energy and transmit signals to the nervous system.
• Sensory reception begins with the detection of stimulus energy by sensory receptors.
  – **Exteroreceptors** detect stimuli originating outside the body.
  – **Interoreceptors** detect stimuli originating inside the body.
  – Sensory receptors convey the energy of stimuli into membrane potentials and the transmit signals to the nervous system.
    • This involves: sensory transduction, amplification, transmission, and integration.
• **Sensory Transduction**
  
  – The conversion of stimulus energy into a change in membrane potential.
  
  – **Receptor potential**: a sensory receptor’s version of a graded potential.

• **Amplification**
  
  – The strengthening of stimulus energy that is can be detected by the nervous system.
    
    • May be a part of, or occur apart from, sensory transduction.
• Transmission.
  – The conduction of sensory impulses to the CNS.
  – Some sensory receptors must transmit chemical signals to sensory neurons.
  – Some sensory receptors are sensory neurons.

• Integration
  – The processing of sensory information.
    • Begins at the sensory receptor.
      – For example, sensory adaptation is a decrease in responsiveness to continued stimulation.
      – For example, the sensitivity of a receptor to a stimulus will vary with environmental conditions.
Sensory receptors are categorized by the type of energy they transduce.
• **Mechanoreceptors** respond to mechanical energy.
  – For example, *muscle spindles* is an interoreceptor that responds to the stretching of skeletal muscle.
  – For example, *cilia* detect motion.

• **Thermoreceptors** respond to heat or cold.

• **Electromagnetic receptors** respond to electromagnetic energy.
  – *Photoreceptors* respond to the radiation we know as visible light and UV radiation.
• **Chemoreceptors** respond to chemical stimuli.
  – General chemoreceptors transmit information about total solute concentration.
  – Specific chemoreceptors respond to specific types of molecules.
  – Internal chemoreceptors respond to glucose, O$_2$, CO$_2$, amino acids, etc.
  – External chemoreceptors are **gustatory receptors** and **olfactory receptors**.
Chemo/mechano-sensitive hair in a spider (Arthropoda: Arachnida)

From Foelix (1996)
Many invertebrates have gravity sensors

- **Statocysts** are mechanoreceptors that function in an invertebrate's sense of equilibrium.
  - Statocysts function is similar to that of the mammalian utricle and saccule.
Sensory apparatus in Cnidaria

- Ocellus or pigment spot in groups other than Hydroids
- Complex eyes with a lens in the box jellies
- Statocysts that function to allow animal to maintain orientation
Aurelia sp. (Cnidaria: Scyphozoa)
Details of Rhopalium in Scyphozoa
Sensory Apparatus in Ctenophora

- Statocyst that functions to coordinate beat of cilia on comb rows to coordinate locomotion and feeding
• A planarian has a head with a pair of eyespots to detect light and lateral flaps that function mainly for smell.
• The planarian nervous system is more complex and centralized than the nerve net of cnidarians.
  – Planarians can learn to modify their responses to stimuli.
A diversity of photoreceptors has evolved among invertebrates

- **Eye cups** are among the simplest photoreceptors
  - Detect light intensity and direction — no image formation.
  - The movement of a planarian is integrated with photoreception.
• Image-forming eyes.
  – **Compound eyes** of insects and crustaceans.
  • Each eye consists of **ommatidia**, each with its own light-focusing lens.
  • This type of eye is very good at detecting movement.
- **Single-lens eyes** of invertebrates such as jellies, polychaetes, spiders, and mollusks. The eye of an octopus works much like a camera and is similar to the vertebrate eye.
• Cephalopods use rapid movements to dart toward their prey which they capture with several long tentacles.
  
  – Squids and octopuses have a well developed single-lens eye, are nearsighted, and have color vision

![Cephalopods Image](image-url)
Vertebrates have single-lens eyes

- Is structurally analogous to the invertebrate single-lens eye.
• Arthropods have well-developed sense organs, including eyes for vision, olfactory receptors for smell, and antennae for touch and smell.
  – Most sense organs are located at the anterior end of the animal, showing extensive cephalization.
Some Butterflies can detect UV Radiation reflected by plants and other insects.
• Sound sensitivity in insects depends on body hairs that vibrate in response to sound waves.
  – Different hairs respond to different frequencies.
• Many insects have a tympanic membrane stretched over a hollow chamber.
Ear of a Noctuid moth (Lepidoptera: Noctuidae)
Perceptions of taste and smell are usually interrelated

- Taste receptors in insects are located on their feet.
Behavior stimulated by Sensory Information often requires CNS Integration

• Feeding responses in insects are not reflex, CNS processes chemosensory data prior to behavior

• Removal of particular chemosensory cells does not necessarily alter feeding responses

• CNS integrates chemosensory information from a variety of cells that respond to stimulate or inhibit feeding
Processing and Integration of sensory information provides a basis for complex behavior

- Foraging
- Predator Avoidance
- Mate location
- Mate attraction
- Mate choice
- Kin recognition
- Relocation of nests sites

- Migration
- Deception
- Territoriality
- Parental care
- Cooperation
Ultrasound production by male whistling moths for mate attraction
Mate choice by females based on symmetry in a wolf spider
Recognition of kin by *Polistes* wasps
Nest relocation by Beewolf wasps
Nest relocation based on spatial memory
Nest relocation by a foraging ant
Migration in the Monarch Butterfly
Migration in Squids
Orchid deception and Thynnine wasps learning to avoid orchids
Female *Photuris* firefly eating male *Photinus* Firefly captured by use of deception
Phoresy and Territoriality in Pseudoscorpions
Territoriality a function of energy reserves in a damselfly
Parental care - Egg brooding by Giant Water Bugs (Belostomatidae)
Mate guarding by the blue milkweed beetle

![Graph showing fitness of male vs. percentage of offspring fathered by last male. The graph compares guarding and not guarding scenarios. Guarding shows a higher fitness trend compared to not guarding.](image-url)
Monogamy in Clown Shrimp
The concept of inclusive fitness can account for most altruistic behavior

- Most social behaviors are selfish, so how do we account for behaviors that help others?
  - **Altruism** is defined as behavior that might decrease individual fitness, but increase the fitness of others.
Inclusive fitness: How can a bee worker enhance its fitness by helping other members of the population?

- How is altruistic behavior maintained by evolution?
- If related individuals help each other, they are in effect helping keep their own genes in the population.
- **Inclusive fitness** is defined as the affect an individual has on proliferating its own genes by reproducing and helping relatives raise offspring.
Hamilton’s Rule and kin selection.

- William Hamilton proposed a quantitative measure for predicting when natural selection would favor altruistic acts.
- Hamilton’s rule states that natural selection favors altruistic acts under certain circumstances.

The rule is as follows:

- \( rB > C \) (where \( r \) will be a fraction)
- The more closely related two individuals are, the greater the value of altruism.
The three key variables in Hamilton’s rule are as follows:

- $B$ is the benefit to the recipient
- $C$ is the cost to the altruist
- $r$ is the coefficient of relatedness, which equals the probability that a particular gene present in one individual will also be inherited from a common parent or ancestor in a second individual.

Kin selection is the mechanism of inclusive fitness, where individuals help relatives raise young.
Haplodiploidy and the Evolution of Social behavior

• Under Hamilton’s rule animal species that have higher coefficients of relatedness among parents and offspring or among siblings, should be more likely to evolve social behavior

• In the Hymenoptera (Ants, Bees, and Wasps) males are haploid (1 set of chromosomes received from mother) and females are diploid (2 sets of chromosomes one set from the mother and one from the father)

• Haplodiploidy leads to asymmetrical coefficients of relatedness
(A) Mother–offspring genetic relatedness

Foundress female genotype

Chromosome A
Chromosome B

Female gametes (eggs)

Equally probable offspring (females)

(a)  (b)  (c)  (d)

Male gametes stored in female

Male gametes

Each daughter shares 50% of her chromosomes (and thus her genes) with her mother

(B) Sister–sister genetic relatedness

Pick any daughter genotype and compare it with the possible genotypes of her sisters

For example:

(c)  (a)  Genetic similarity

(c)  (a)  75% (3 of 4 chromosomes)

(b)  75%

(c)  100%

(d)  50%

Average = 75% of genes shared between sisters
## Coefficients of Relatedness

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<th>Haplodiploid Species</th>
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<td>• Father – Son</td>
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<td>• Father – Son (0)</td>
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<tr>
<td>• Sisters</td>
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<td>• Brothers</td>
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Social Behavior in Invertebrates

- **Parental Care** (provision of food defense from predators)
- **Bi-parental care** (cooperation between mates)
- Communal nesting
- Schooling to avoid predators
- Cooperation in brood care between parents and offspring
Levels of Sociality

- **Solitary**
- **Subsocial** – adults care for their own young
- **Communal** – members of same generation use same composite nest without cooperating in brood care
- **Quasisocial** – members of same generation use same composite nest and cooperate in brood care
- **Semisocial** – also a reproductive division of labor (a worker and reproductive caste)
- **Eusocial** – also overlap in generations so that offspring assist parents
Development of Eusocial Behavior in Invertebrates

• Sociality most developed among the in Insecta in the Hymenoptera (ants, bees and wasps) and Isoptera (Termites)
• Some social spiders, but not more correctly classified as communal or quasisocial
Not all Hymenoptera are Eusocial

Aculeate Hymenoptera

Wasps

Bees
Sterile castes in some social insects

Termite soldiers that spray sticky and repellent fluids

Tiny Worker and Large Soldier Ant
Weaver ant bivouac (*Oecophylla sp*)
Similarities in Social Behavior Between Termites and Social Hymenoptera

- Castes similar in number and kind
- Exchange of liquid food occurs
- Chemical trails used in recruitment
- Inhibitory caste pheromones exist
- Grooming between individuals occurs
- Nest odor and territoriality occur
- Nest structure is comparably complex
- Cannibalism is widespread
Differences in Social Behavior Between Termites and Social Hymenoptera

**Termites**
- Caste determined based on pheromones
- Workers are male and female
- Larvae and nymphs labor
- No dominance hierarchies
- Social parasitism between species absent
- Exchange of liquid anal food universal
- “King” stays in the house

**Eusocial Hymenoptera**
- Caste determination based on nutrition
- Workers all female
- Larvae and pupae are helpless
- Dominance hierarchies common
- Social parasitism between species common
- Exchange of liquid anal food rare, trophic eggs occur
- “King” leaves the building
Summary

• Trend toward increasing cephalization (concentration of sensory and nervous structures in anterior of body) in invertebrates
• Trend of increasing integration of sensory information by CNS
• Rapid development of a variety of sensory capabilities
• Development of complex behaviors based on sensory information
• Development of sub-social and social behaviors