Locomotion

CSE169: Computer Animation

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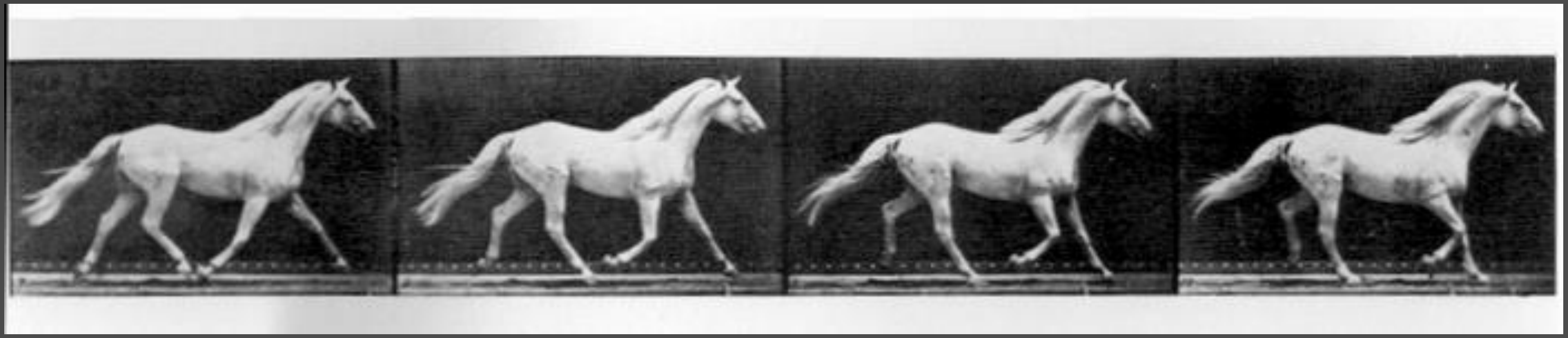
UCSD, Spring 2016

Legged Locomotion

Muybridge

- Eadweard Muybridge
- “Animal Locomotion” - 1887
- “Animals in Motion” - 1899
- “The Human Figure in Motion” - 1901



Gaits

- A *gait* refers to a particular sequence of lifting and placing the feet during legged locomotion (gallop, trot, walk, run…)
- Each repetition of the sequence is called a *gait cycle*
- The time taken in one complete cycle is the *gait period*
- The inverse of the period is the *gait frequency* (1/period)
- Normally, in one gait cycle, each leg goes through exactly one complete step cycle

Gait Phase

- We can think of the *gait phase* a value that ranges from 0 to 1 as the gait cycle proceeds
- We can choose 0 as being any arbitrary point within the cycle (such as when the back left foot begins its step)
- The phase is like a clock that keeps going round and round (0…1, 0…1, 0…1)
- For a particular gait, the stepping of the legs and all other motion of the character can be described relative to the gait phase

Step Cycle

- In one gait cycle, each individual leg goes through a complete *step cycle*
- Each leg's step cycle is phase shifted relative to the main gait cycle
- The step cycle is broken into two main stages
  - *Support stage* (foot on ground)
  - *Transfer stage* (foot in the air)
- The amount of time a leg spends in the support stage is the *support duration* (& likewise for *transfer duration*)

$$SupportDuration + TransferDuration = GaitPeriod$$

Duty Factor

- The relative amount of time a foot spends on the ground is called the *duty factor*

$$DutyFactor = \frac{SupportDuration}{GaitPeriod}$$

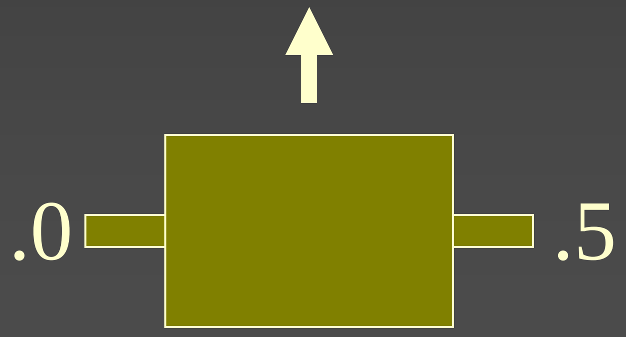
- For a human walking, the duty factor will be greater than 0.5, indicating that there is an overlap time when both feet are on the ground
- For a run, the duty factor is less than 0.5, indicating that there is a time when both feet are in the air and the body is undergoing ballistic motion

Step Phase

- The *step phase* is a value that ranges from 0 to 1 during an individual leg's step cycle
- We can choose 0 to indicate the moment when the foot begins to lift (i.e., the beginning of the transfer phase)
- The foot contacts the ground and comes to rest when the phase equals 1 minus the duty factor

Step Trigger

- Each leg's step cycle is phase shifted relative to the main gait cycle
- This phase shift is called the *step trigger*
- The trigger is the phase within the main gait cycle where a particular leg begins its step cycle



Biped Walk

Locomotion Terminology

- Gait
  - Gait cycle
  - Gait period
  - Gait frequency
  - Gait phase
- Stepping
  - Step cycle
  - Step phase
  - Support stage, support duration
  - Transfer stage, transfer duration
  - Duty factor
  - Step trigger

Gait Description

- A simple description of the timing of a particular gait requires the following information
  - Number of legs
  - Gait period
  - Duty factor & step trigger for each leg

Animal Gaits

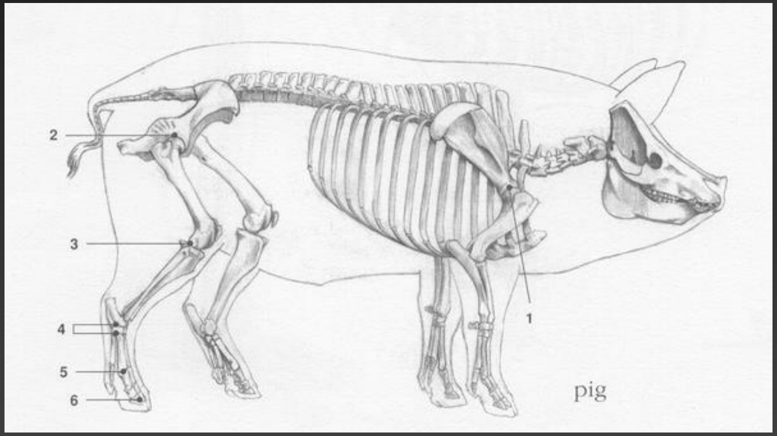
Ancestral Tetrapods

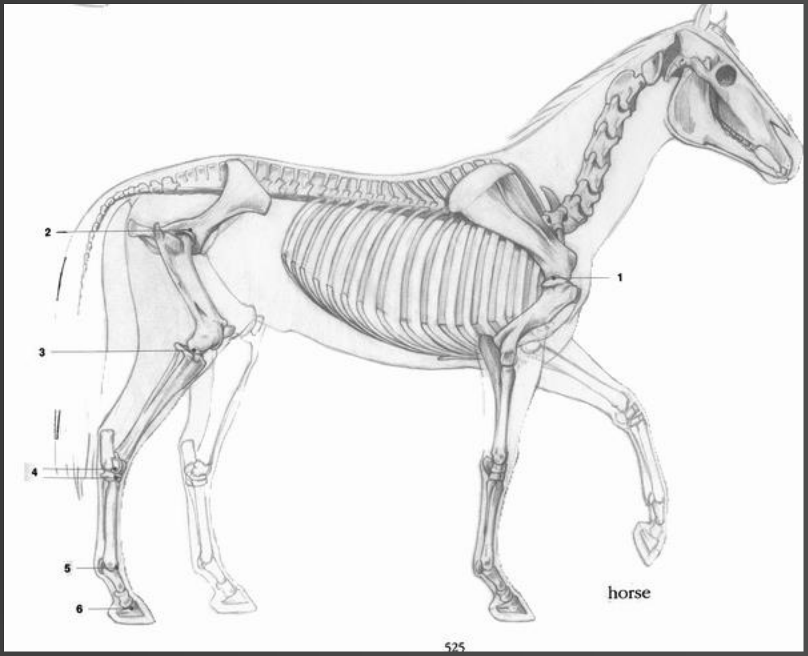
- All land based vertebrates evolved from an original ‘tetrapod’ ancestor
- The tetrapod was like a primitive reptile- closer to a fish
- The 4 legs were adaptations of swimming fins and the creature moved on land by a combination of ‘paddling’ with its legs and ‘swimming’ with it’s spine
- All present day quadruped vertebrates are based on the same underlying construction, but with various adaptations
- Even snakes, birds, dolphins, and whales evolved from the ancestral tetrapod and still show many similarities

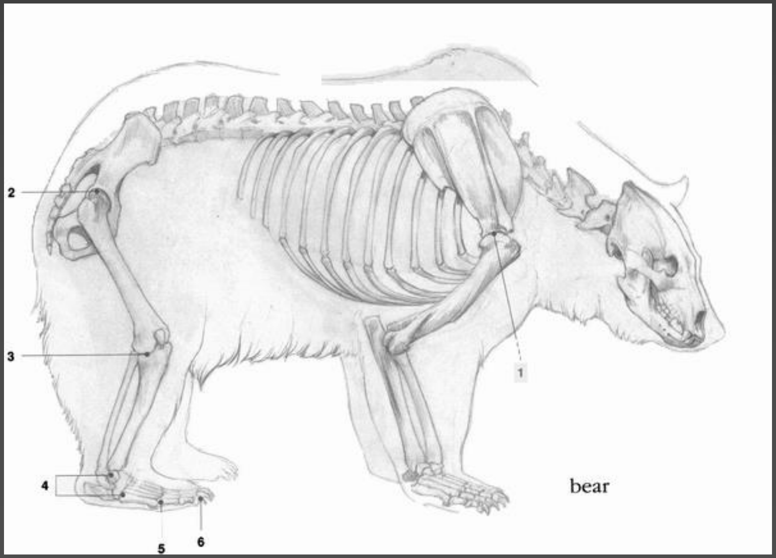
Quadruped Construction

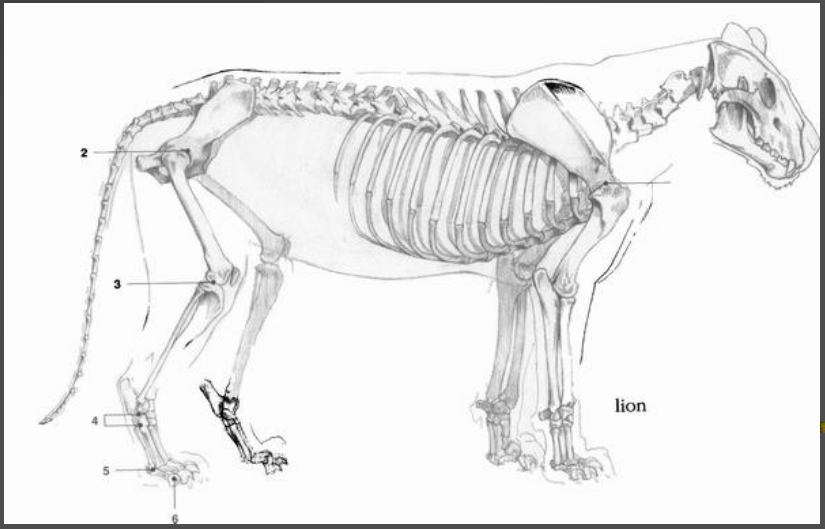
- Arms
  - Clavicle
  - Scapula
  - Humerus
  - Radius/Ulna
  - Carpals
  - Metacarpals
  - Phalanges
- Legs
  - Pelvis
  - Femur
  - Tibia/Fibula
  - Tarsals
  - Metatarsals
  - Phalanges

Quadrupeds



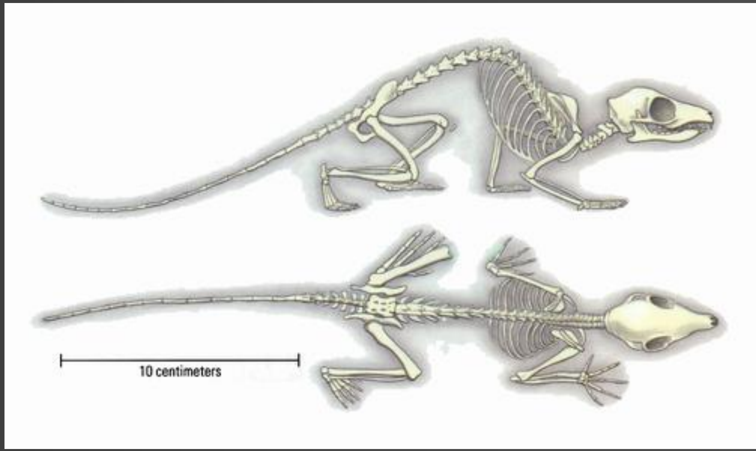


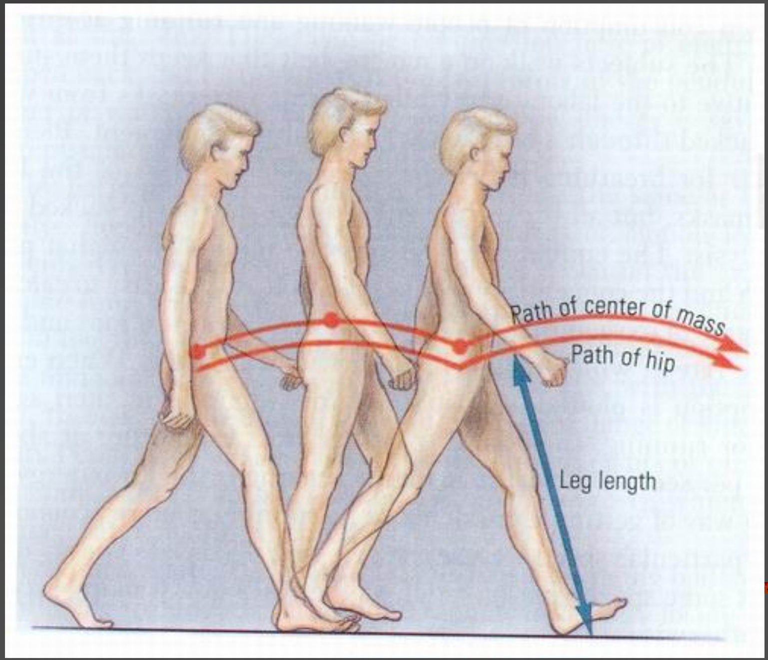




Stances

- Some animals, such as humans and bears walk flat footed (palmate)
- Some, like horses and cattle walk more on their fingers (digitate)
- Smaller or stockier animals sometimes walk with wide stances (sprawling gaits) (these include insects, many reptiles, and some small mammals)
- Larger animals tend to walk with straighter legs



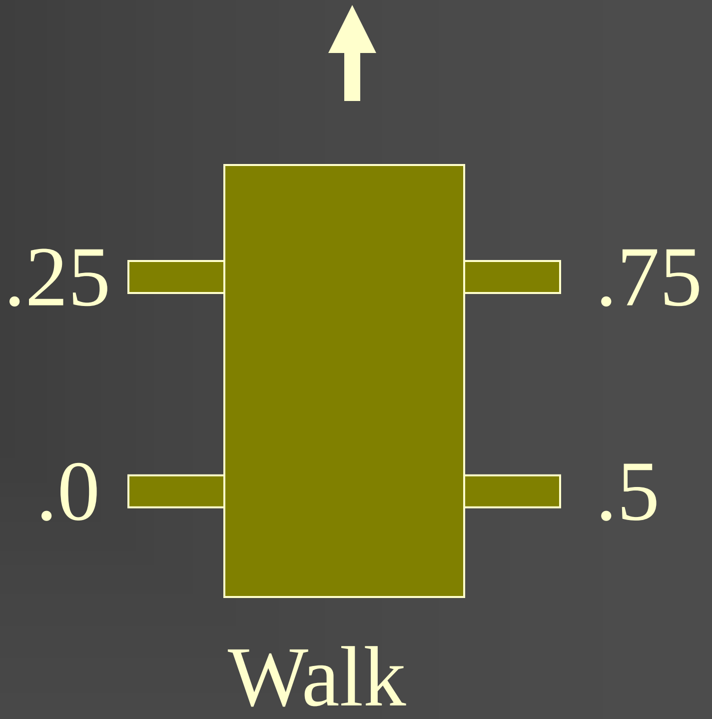


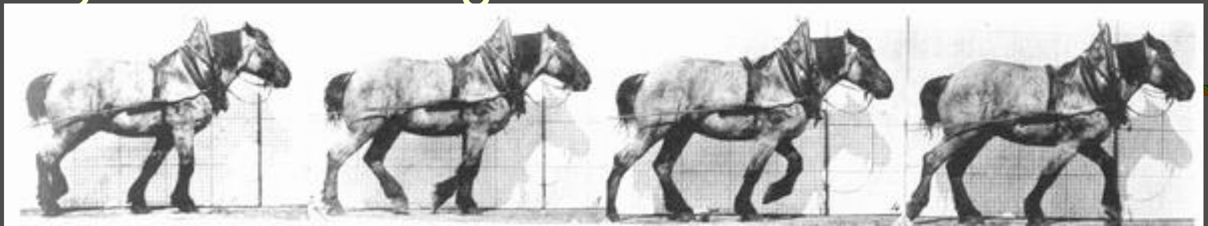
Quadruped Gaits

- Quadruped: 4 legs
- Muybridge showed that almost all quadrupeds use one or more of the following gaits
  - Walk
  - Amble
  - Trot
  - Rack/Pace
  - Gallop (rotary & transverse)
  - Canter

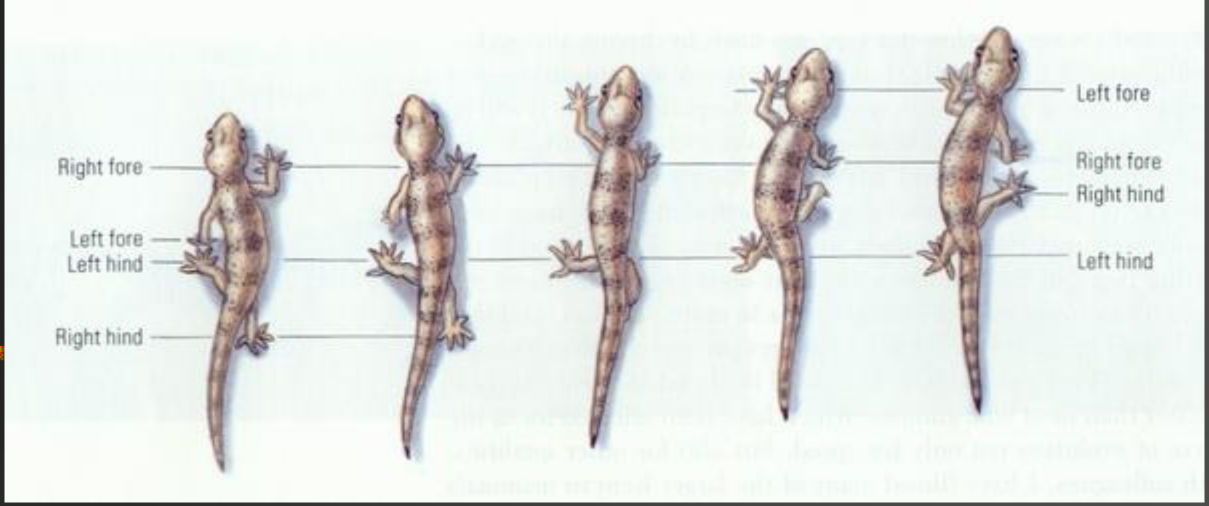
Quadruped Walk

- The basic slow gait of most quadrupeds is the walk
- Very slow walks may involve 3-4 legs on the ground, but normal walks involve 3 legs on the ground with a brief moment with only 2
- The duty factor is therefore relatively high (.6 ~ .8)
- Actual timing of walk gaits may vary from the diagram

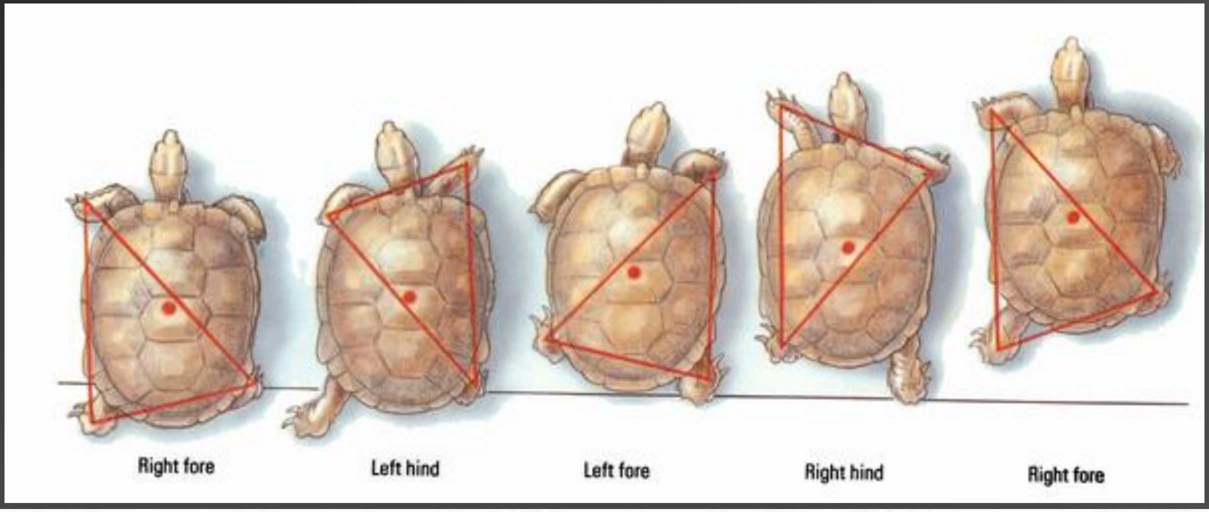




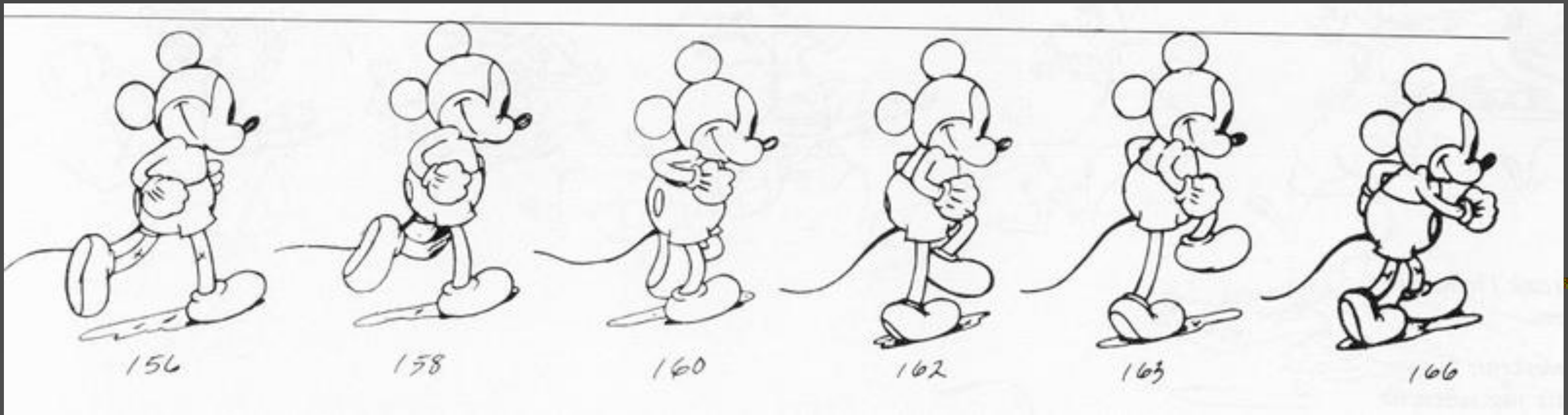
Walks



Right fore
Left fore
Left hind
Right hind
Left fore
Right fore
Right hind
Left hind



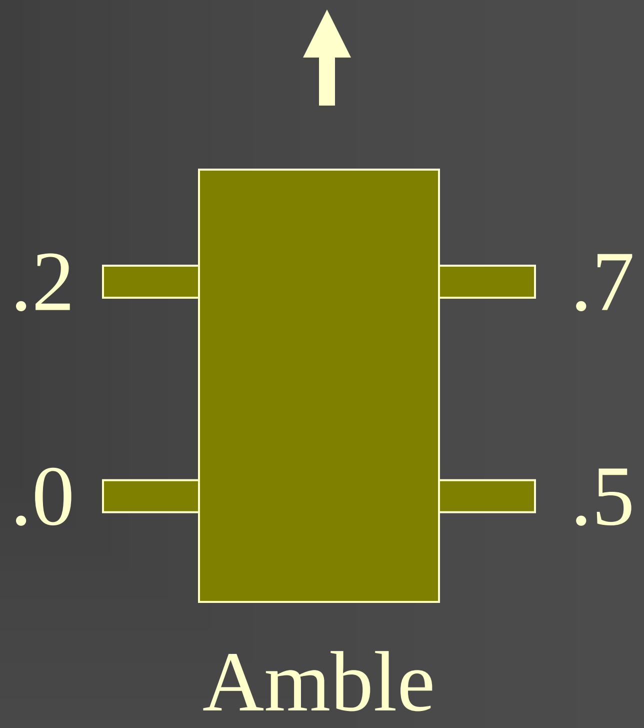
Right fore
Left hind
Left fore
Right hind
Right fore



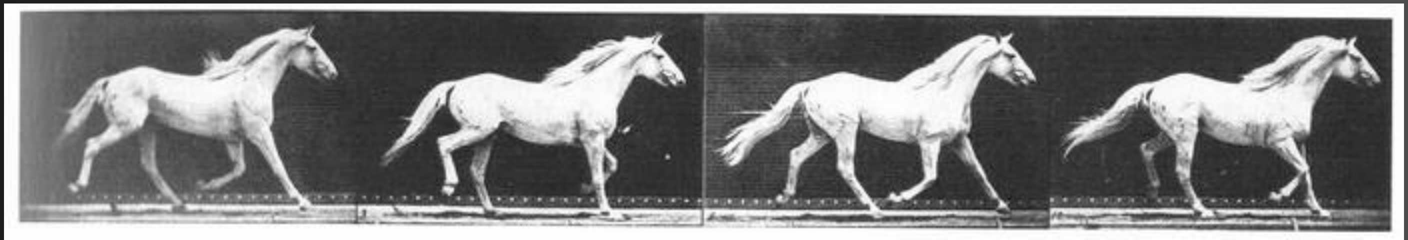
156
158
160
162
163
166

Amble

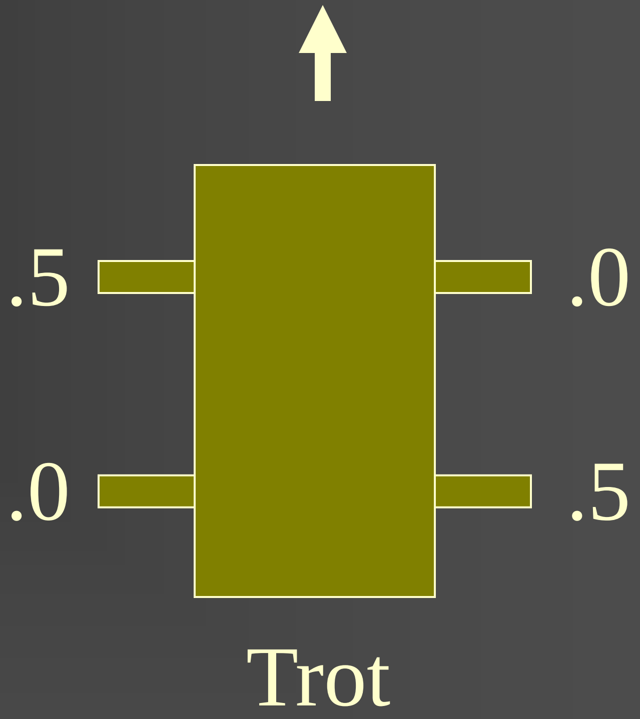
- Ambles are like a quicker version of the walk, but are also associated with larger, slow moving quadrupeds
- The duty factor is often in the .5 ~ .7 range, but some horses amble at even lower duty factors
- Elephants use the amble gait exclusively. The front and back legs are often very close in phase (shifted by around .1 or so)
- The gait often involves a noticeable swinging of the body from left to right



Trot

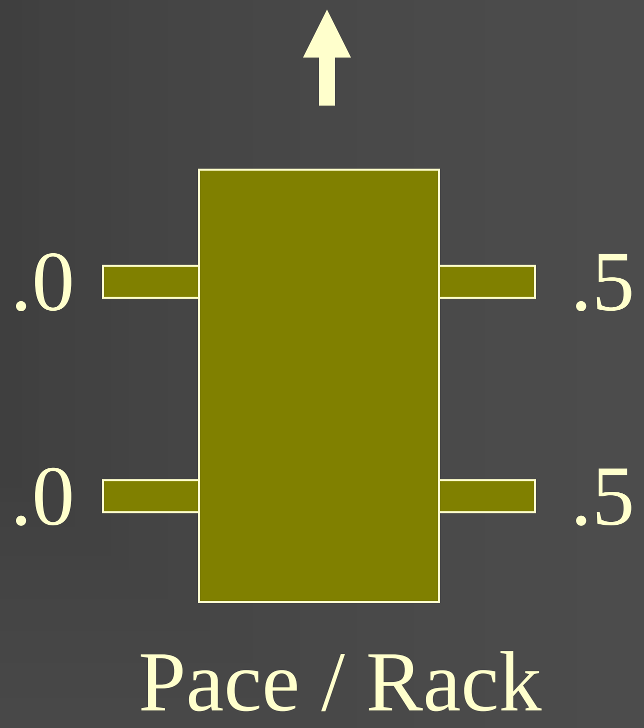


- The trot is a medium paced gait where alternate diagonal legs step nearly in sync (though often slightly led by the forefoot)
- The duty factor is usually relatively low (<.4) and there are moments where all 4 legs are off the ground (actually, cats sometimes trot at a higher duty factor…)
- Before Muybridge, most horse trainers believed a trotting horse always had at least one foot on the ground



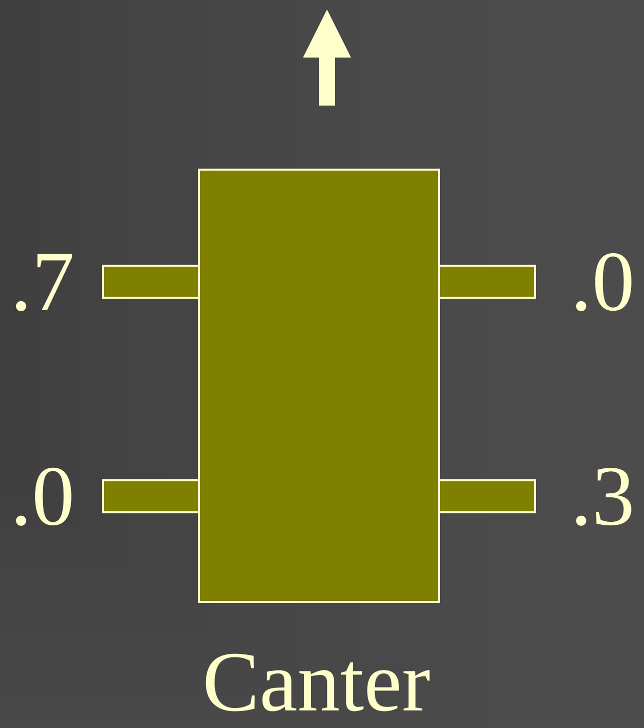
Pace / Rack

- The rack or pace has similar qualities to the trot, but horses are rarely trained to perform this gait
- This gait is considered to be the least comfortable for a rider, but supposedly offers better traction than the trot
- Most camels use this as their primary gait



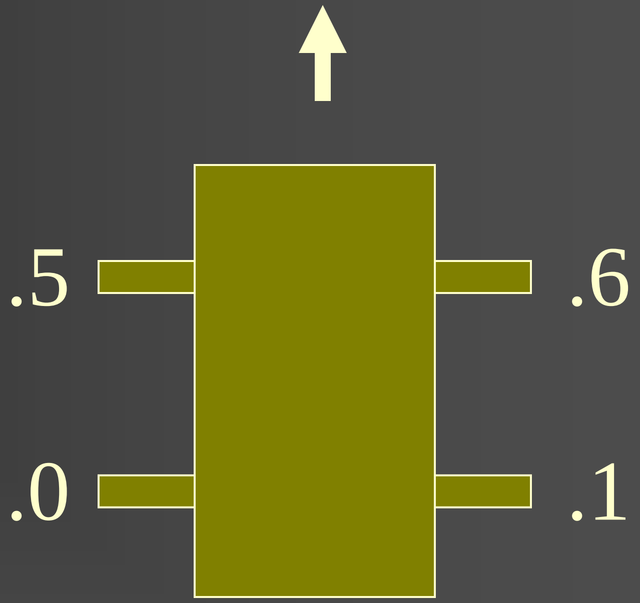
Canter

- Unlike the first 4 quadruped gaits we looked at, the canter is asymmetrical
- The canter is a medium speed gait, but a bit irregular and not usually used for long intervals
- Some horses canter as they slow down from a gallop
- Sometimes, the timing of the canter is more like .6, .0, .0, .1, with 3 legs stepping in rapid succession, alternating with the 4th leg



Transverse Gallop

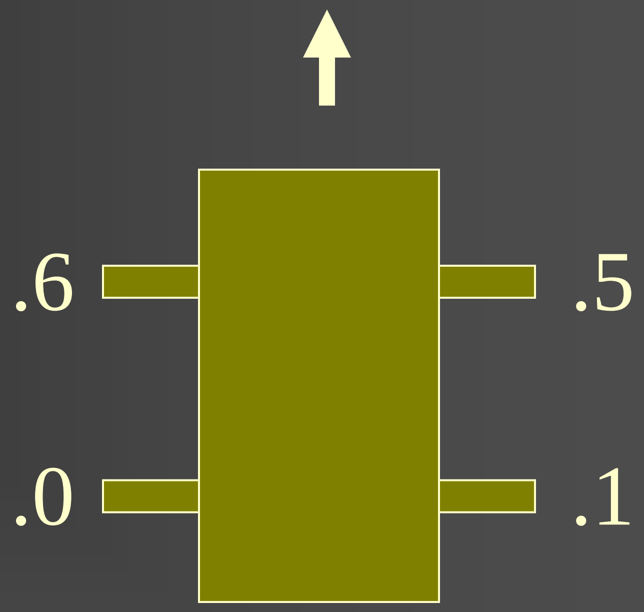
- The gallop is the fastest quadruped gait
- The gallop involves an alternation between the front and back pairs of legs, but slightly out of sync
- There are several subtle variations on gallops, but they are generally separated into transverse and rotary gallops
- Horses tend to prefer the transverse gallop, as do most other quadrupeds



Transverse Gallop

Rotary Gallop

- Rotary gallops involve a circular LR-RL timing (as opposed to the zig-zagging LR-LR timing of the transverse gallop)
- Many dogs use a rotary gallop at high speeds, as do a few other quadrupeds

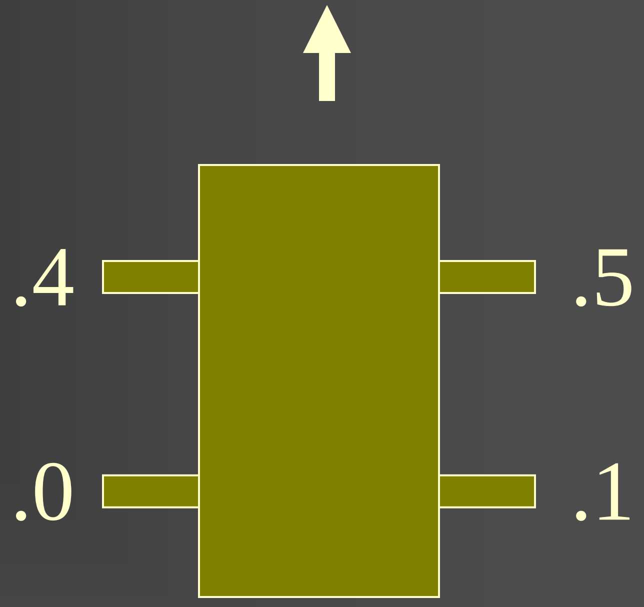


Rotary Gallop

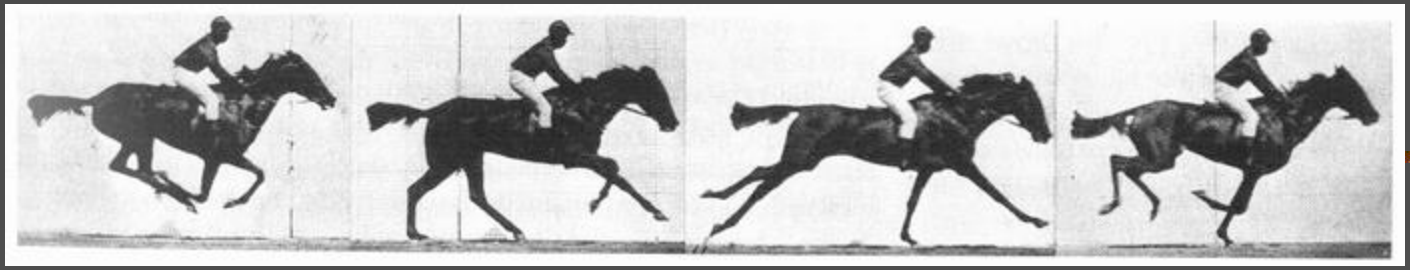
Equestrian Gallop

- Gallops can also be broken into either feline or equestrian types, based on the front/back timing
- For equestrian (horse-type) gallops, the timing is like:

  back-front-pause
- After the front legs push off, all four legs are in the air



Equestrian Gallop

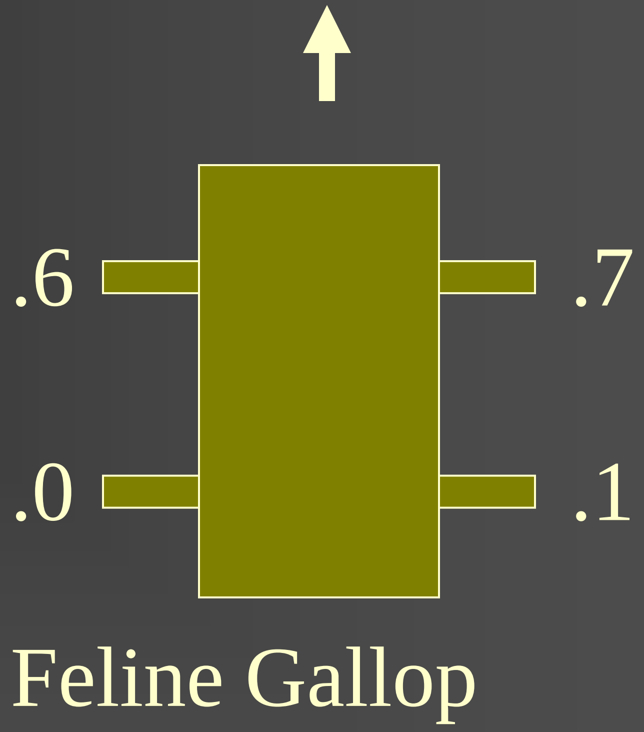


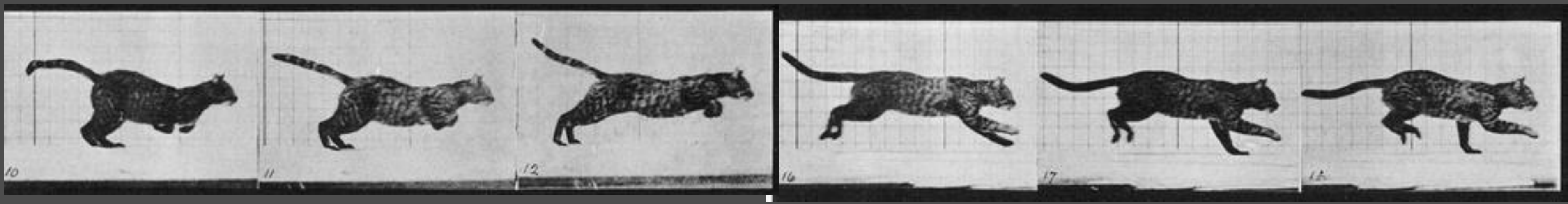
Feline Gallop

- For feline (cat-type) gallops, the timing is like:

  front-back-pause

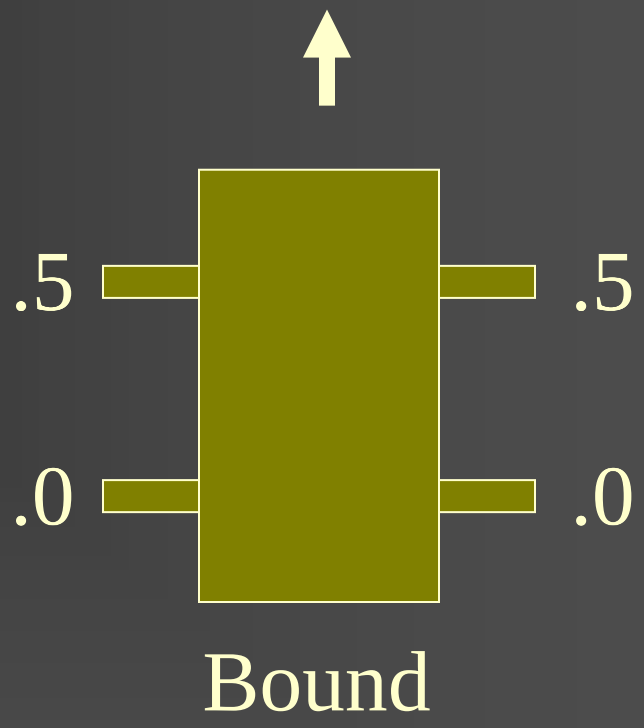
- After the back legs push off, all four legs are in the air
- This sometimes known as a leaping gait

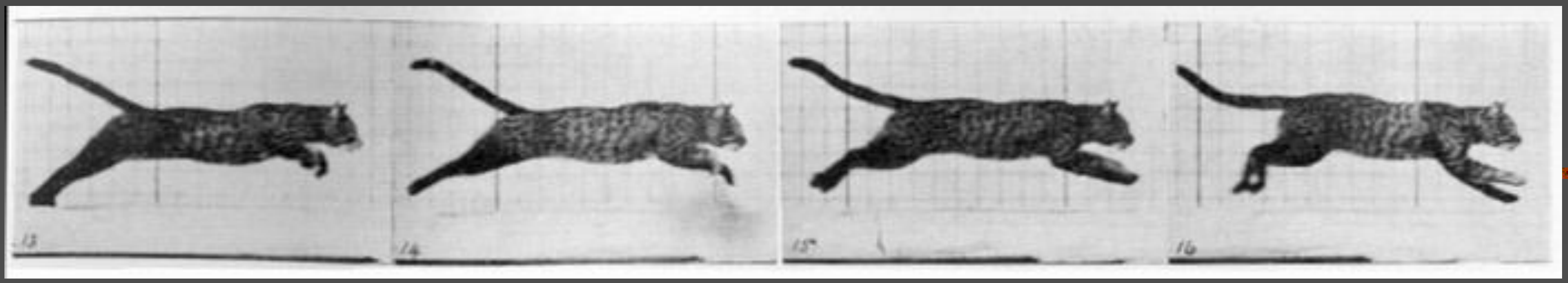




Bound

- Some quadrupeds gallop in such a way that the front and back pairs of legs are in sync
- This is known as a bounding gait

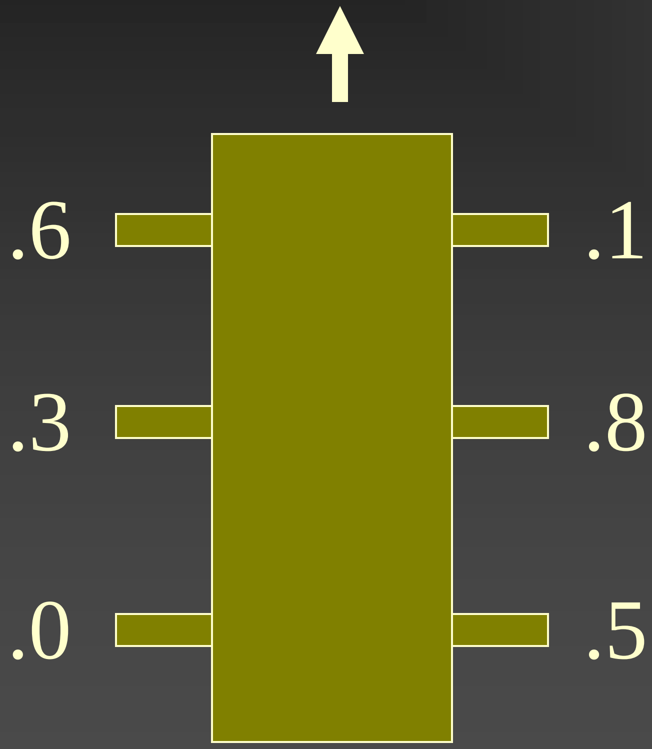




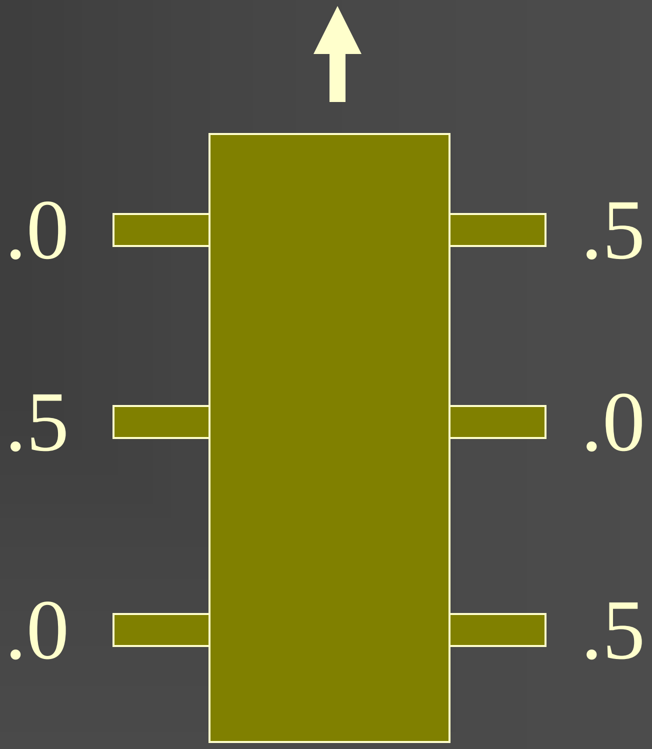
Hexapod Gaits

- Most adult insects are hexapods (6 legs)
- For slow movement, some use an *off-sync back to front wave gait*
- For faster movement, most insects use a *tripod gait*
- Occasionally, one encounters insects that run on their back 4 legs or even only their back 2 (cockroaches can do this)

Hexapod Gaits



Off-sync back to front wave gait

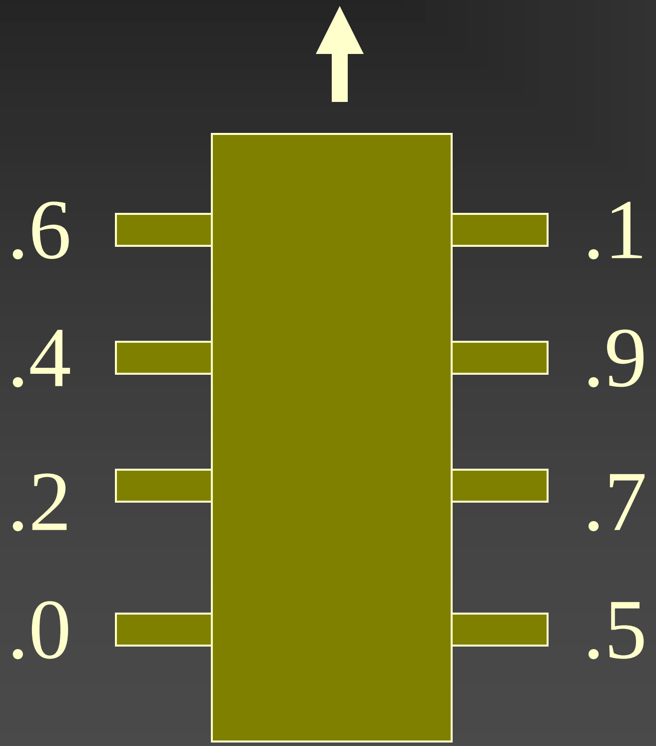


Tripod gait

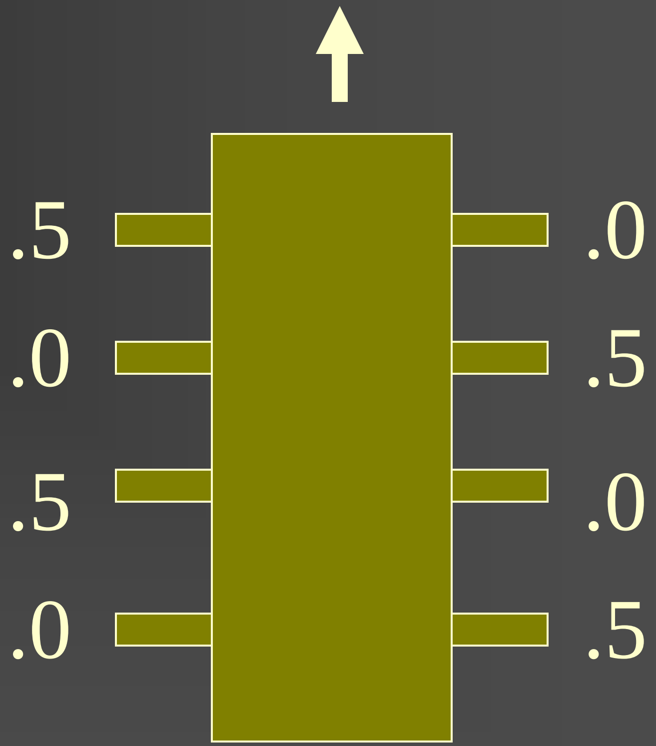
Octapod Gaits

- Spiders are octapods (8 legs)
- They tend to have very similar gaits to hexapods
  - Off-sync back to front wave gait for slow movement
  - Quadrapod gait (not quadruped)

Octapod Gaits



Off-sync back to front wave gait

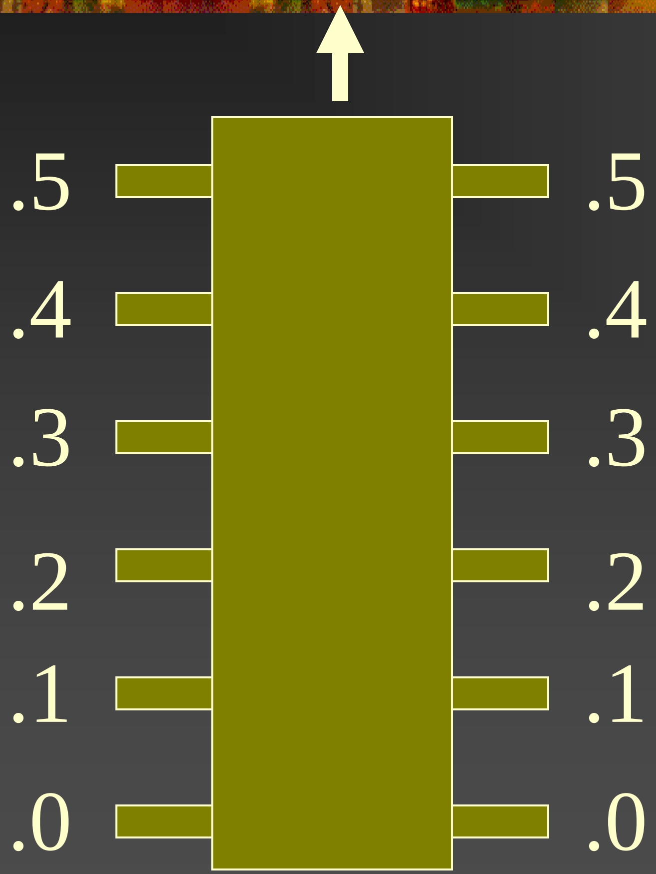


Quadrapod gait

Young Insect Gaits

- Younger insects (larva, grubs, caterpillars) don’t tend to move around as well as the older ones
- Larva and grubs tend to wiggle & dig a lot
- Caterpillars use *ON-sync back to front wave gaits*

Caterpillar Gait

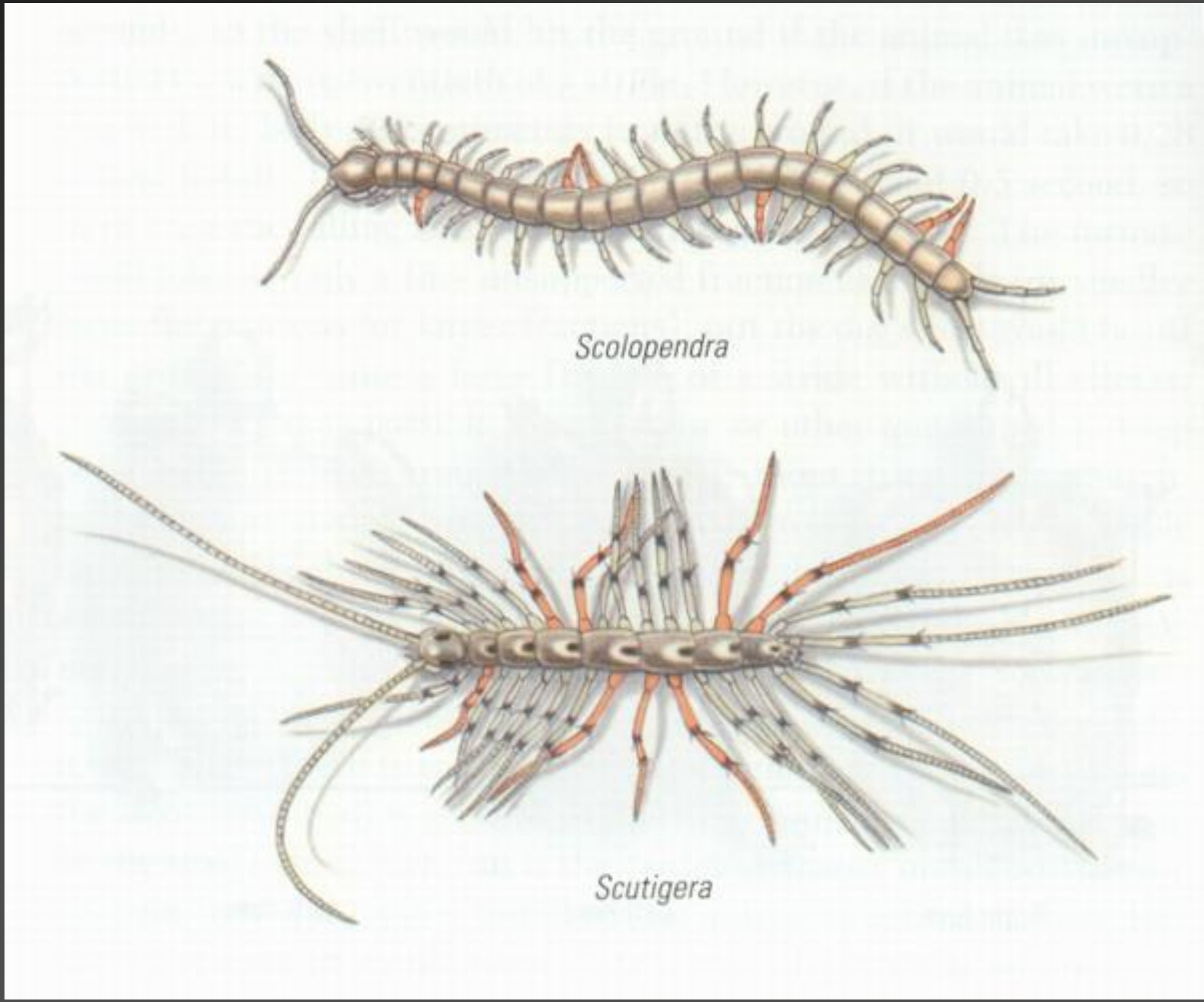


On-sync back to front wave gait

Centipedes & Millipedes

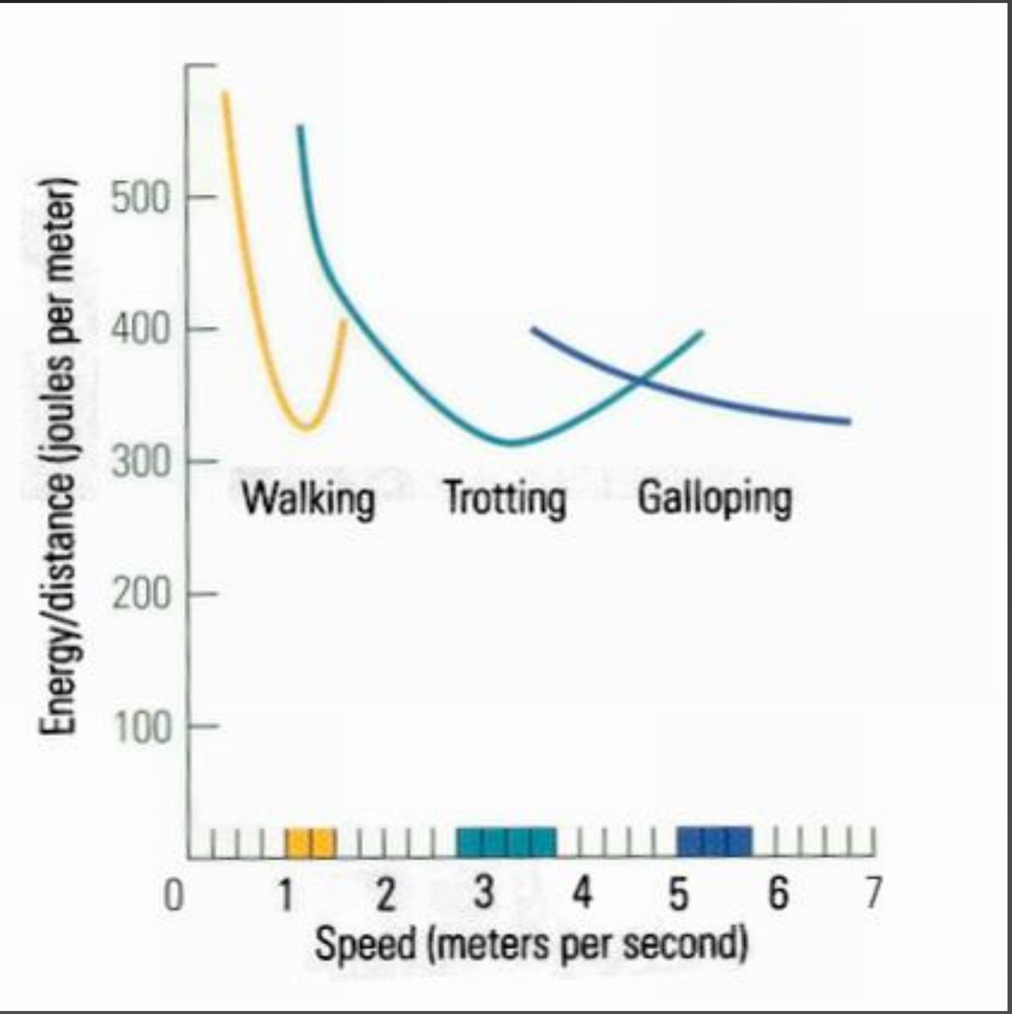
- Centipedes & millipedes tend to use off-sync back to front wave type gaits with several waves
- Some species, however use a front to back wave gait
- When moving fast, their motion tends towards a tripod type gait, alternating between two different sets of three main support zones

Centipedes & Millipedes

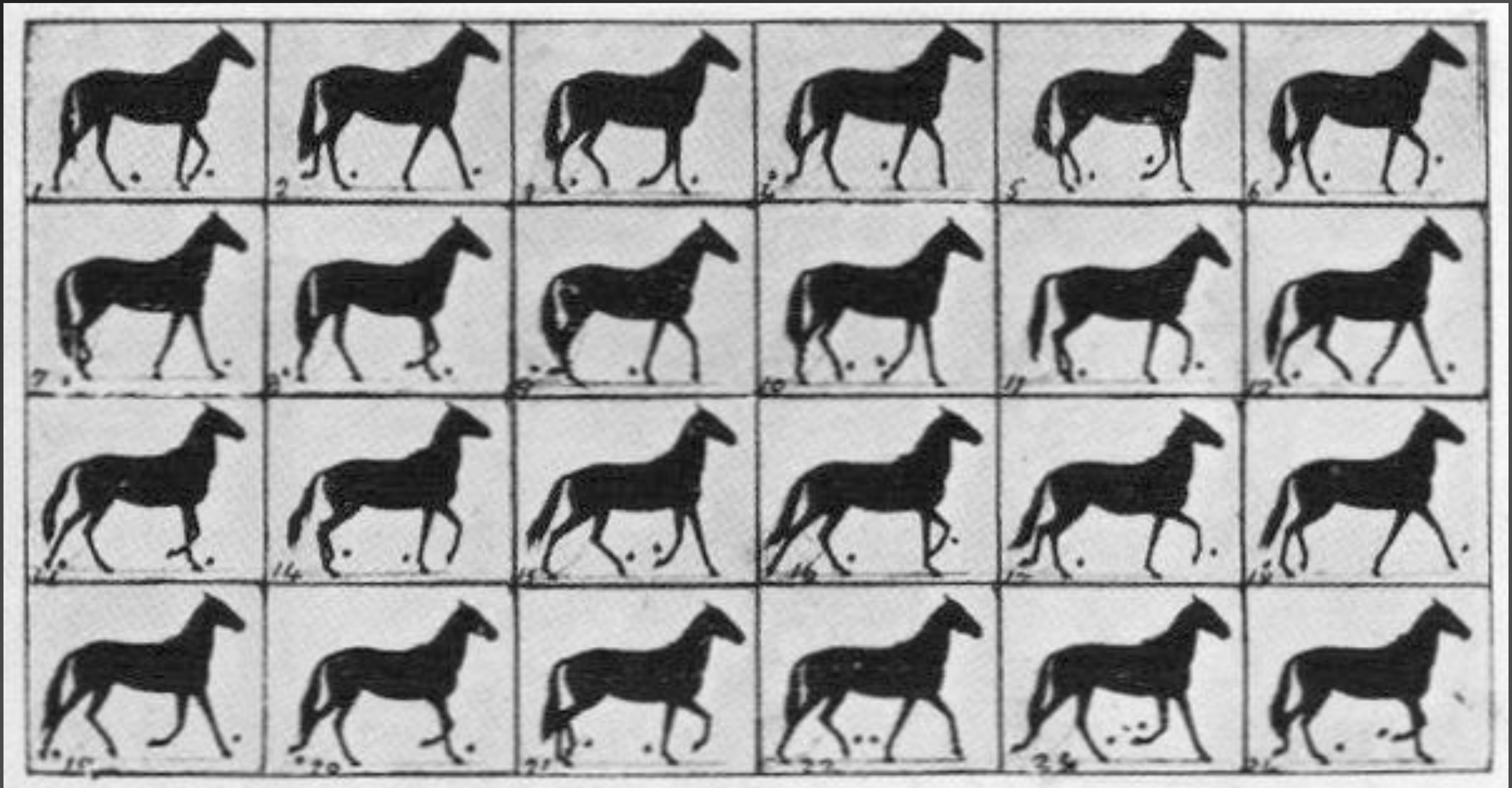


Gait Transitions

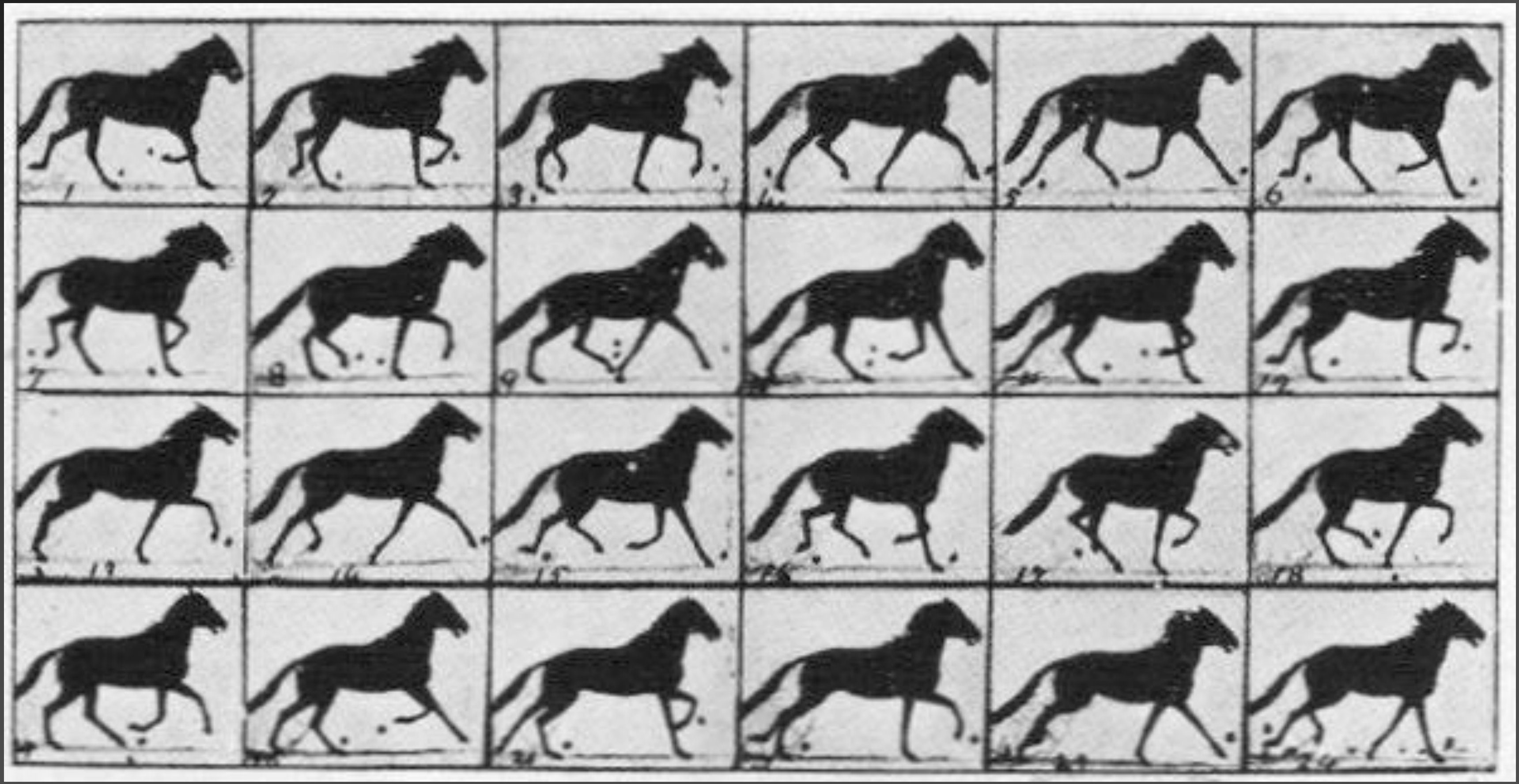
Gait Efficiency



Walk to Trot



Trot to Gallop



Flying

Flight Modes

- Birds use a variety of flight modes that could be compared to gaits
  - Ballistic
  - Gliding
  - Slow flapping
  - Fast flapping
  - Hovering
- Different types of birds tend to favor one mode or another and often switch between modes

Ballistic Flight

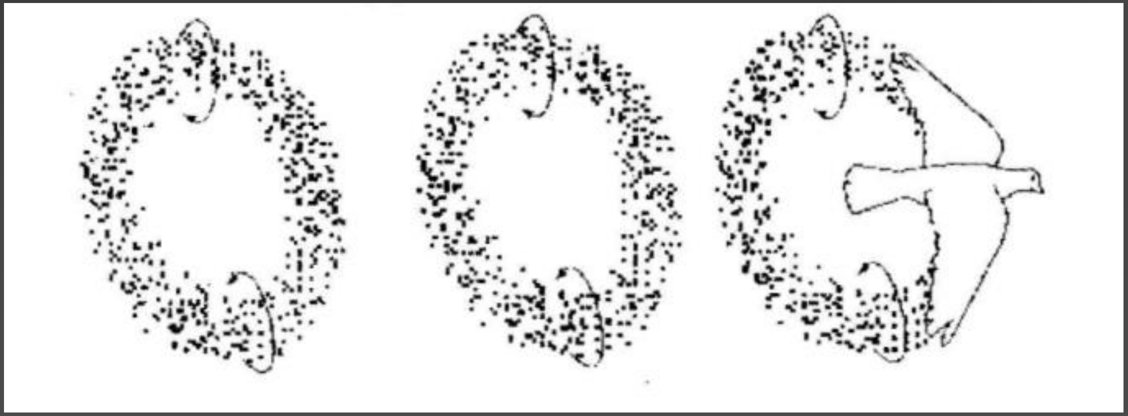
- Ballistic: This refers to the motion of a dead weight or ballast (i.e., parabolic motion)
- This would refer to a bird flying with the wings fully tucked, and so is obviously not sustainable for long periods
- Some birds (like finches) use a *punctuated ballistic* flight, where they briefly flap, then coast in a parabolic path, then flap again to coast the next parabola, etc.

Gliding

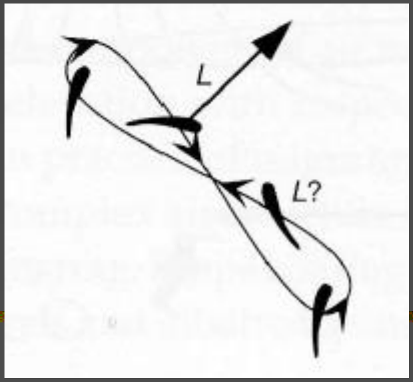
- Gliding is a form of coasting where the wings are held relatively fixed and the tail performs minor course corrections
- In still air, steady state gliding motion will result in constant forward velocity and a gradual loss of altitude according to the glide ratio (horizontal distance / vertical distance)
- Some birds will briefly glide for a few seconds between flapping modes
- *Soaring* refers to the long term gliding flight that may use thermals or other updrafts to stay aloft for long periods without flapping (used by hawks, vultures, pelicans, etc.)

Slow Flapping

- Different flapping modes are characterized by the structure of the wake created in the airflow
- Slow flapping flight is characterized by a wake of separate vortex rings
- Also known as *vortex-ring flight*



- The wings typically move in a figure 8 pattern when viewed from the side



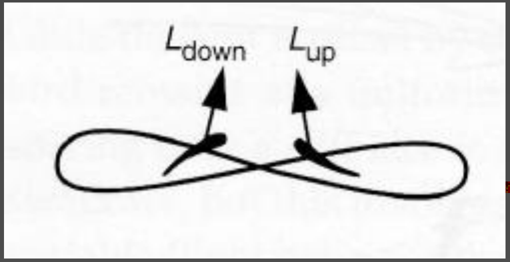
Fast Flapping

- Fast flapping is characterized by producing a wake of two separate but continuous vortices
- Also known as *continuous vortex flight*

- The wings may move in a more elliptical pattern when viewed from the side

Hovering

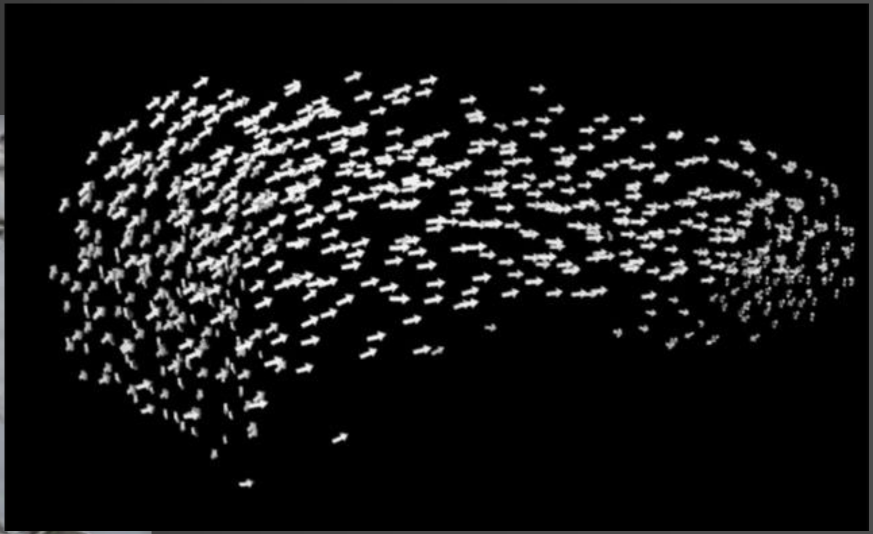
- Some birds are capable of hovering in place and maneuvering around more like a helicopter
- Hummingbirds achieve this with a special adaptation to the shoulder bone that allows it to achieve downward pressure on both the up and down stroke
- When hovering in place, the wings follow a flattened figure 8 pattern

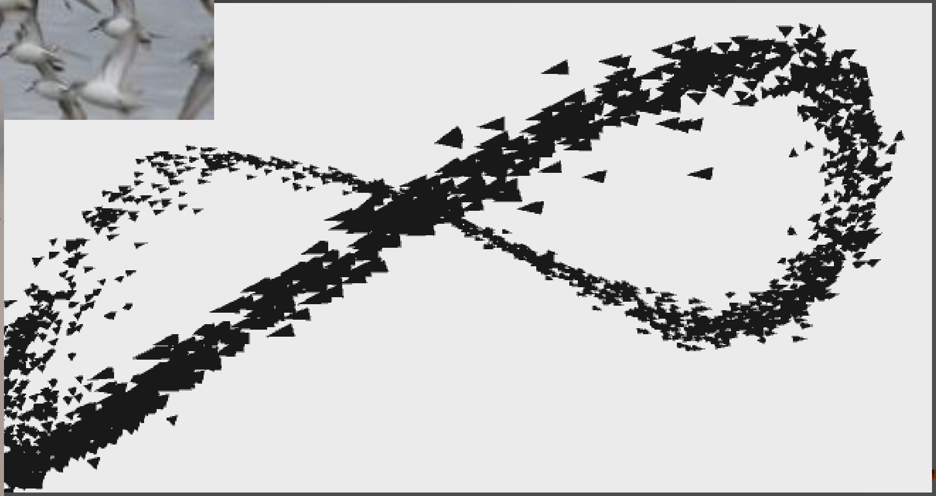


Flocks

- Flocking is one of the more interesting bird behaviors and is related to herding of terrestrial animals, schooling of fish, and even human crowd behavior
- Flocking behavior has been used as a tool in computer animation since its introduction in 1987 by a classic paper by Craig Reynolds
- To model flocking behavior, individual animals only need be aware of a few of the closest other animals in their field of view
- In general, an individual tried to match the average velocity of its nearest neighbors and possibly move towards the center of mass of the nearest neighbors
- This combines with other motivations and perturbations to lead to the combined flock behavior

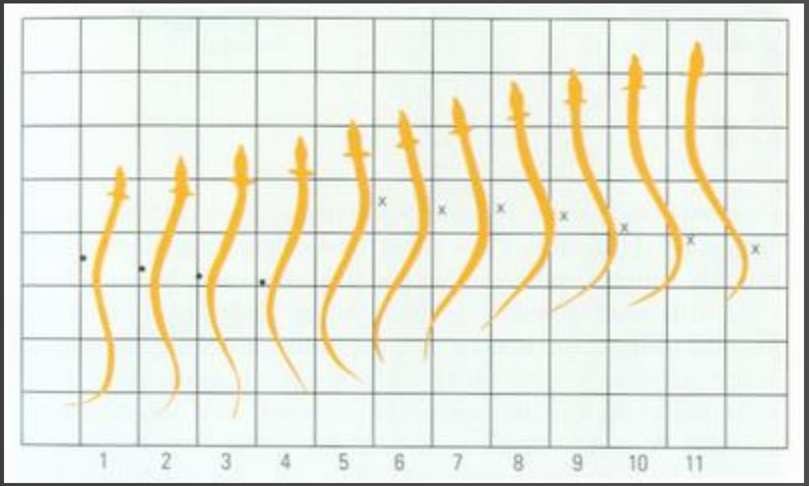
Flocks

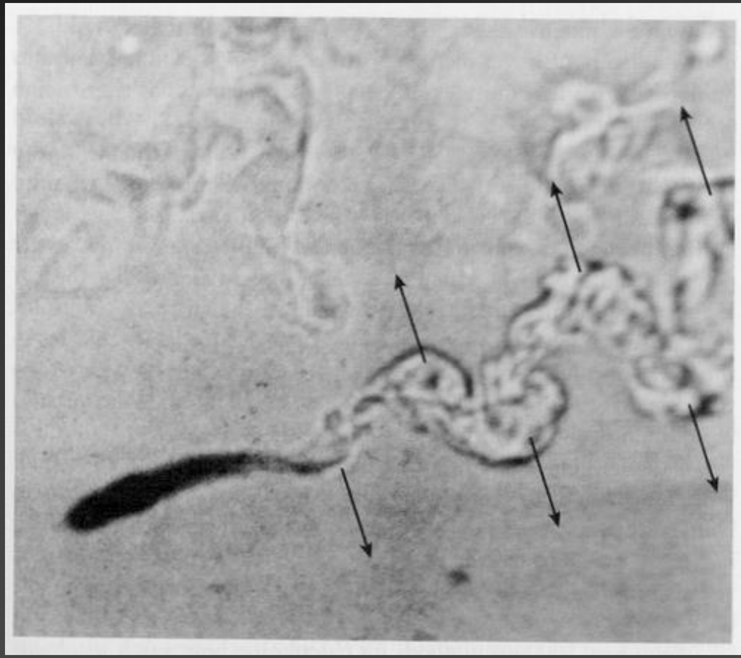


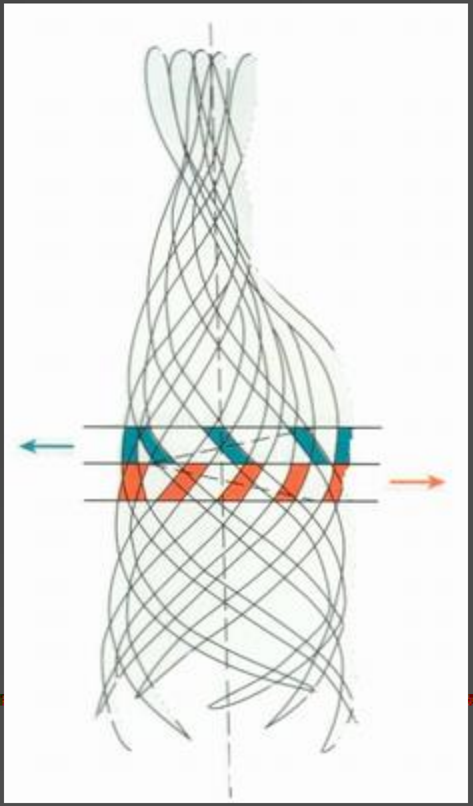


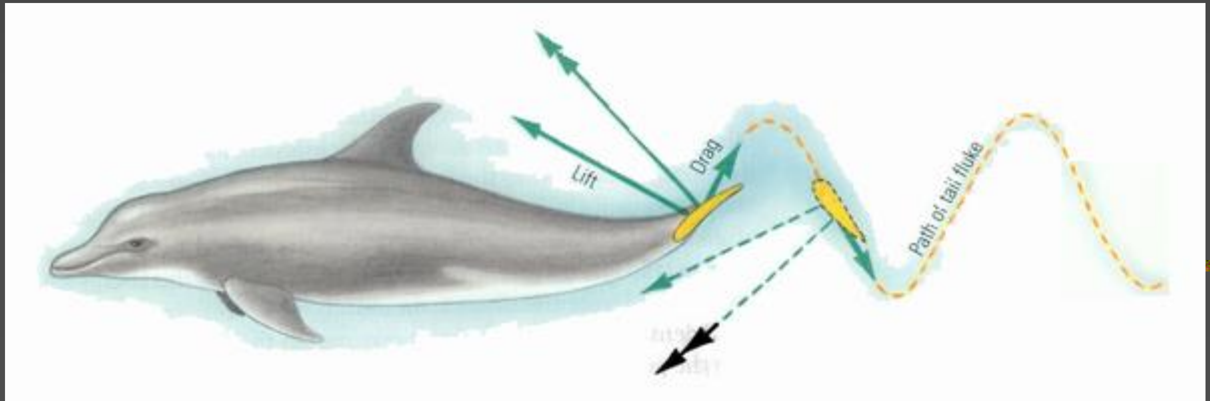
Other Types of Locomotion

Swimming

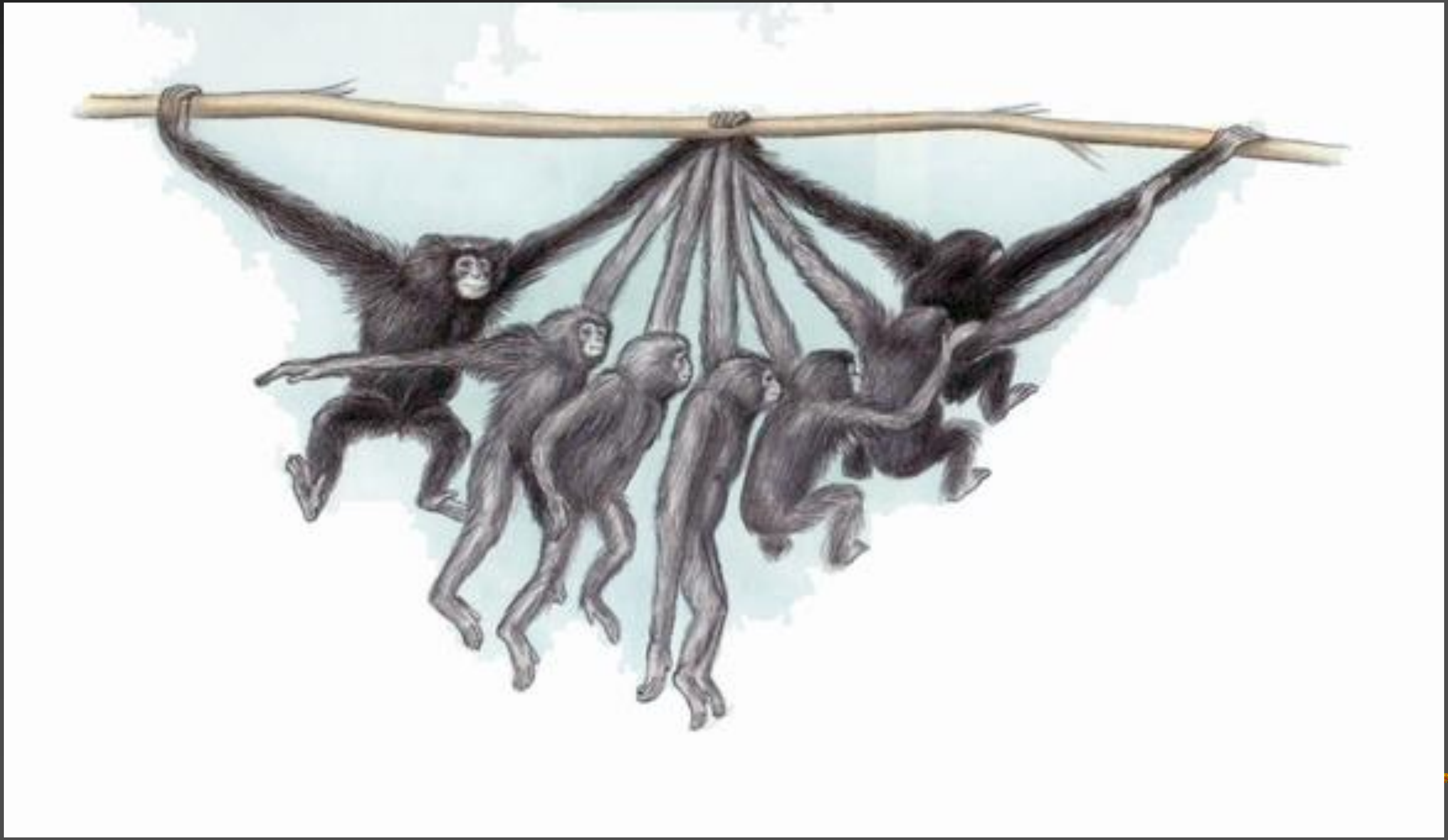




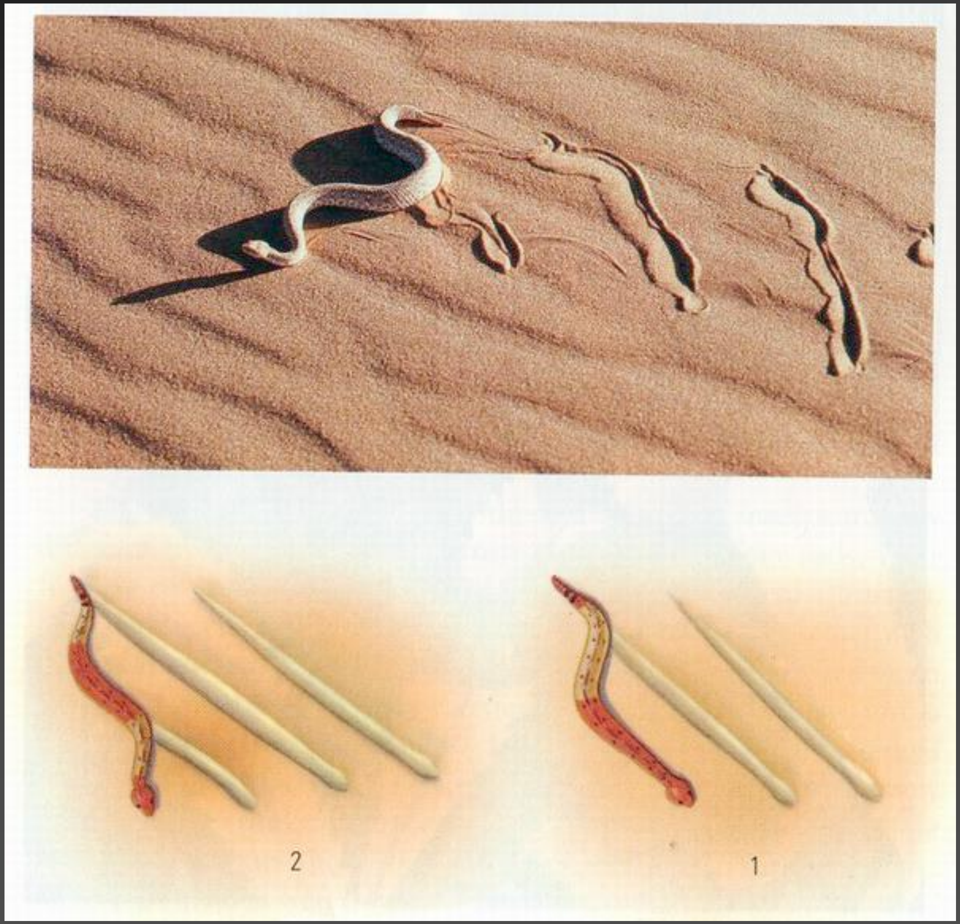




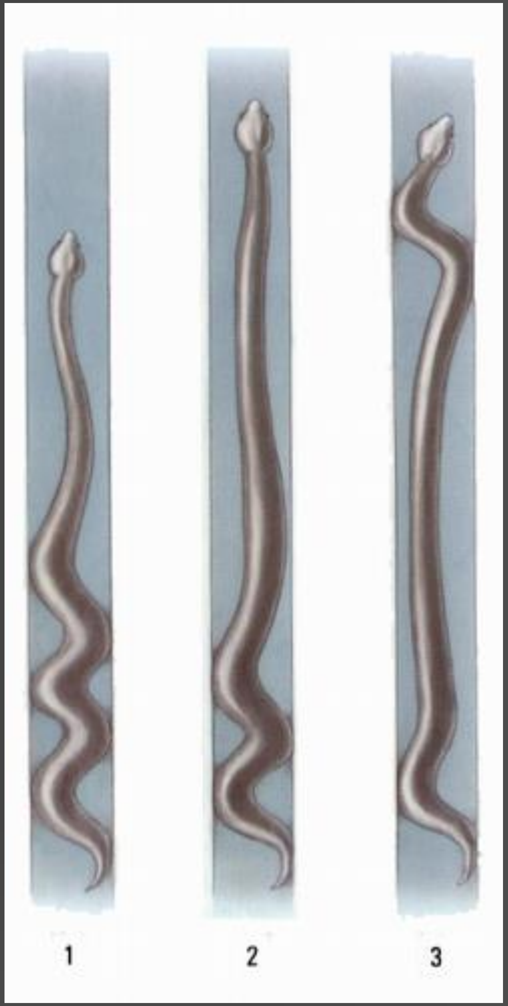
Climbing & Brachiation



Slithering



Sidewinding



Concertina

Slithering

- Snakes
  - Serpentine crawling: rapid front to back waves
  - Sidewinding: front to back waves with strong lateral component. Often optimized for minimal ground contact
  - Concertina locomotion: slower crawling front to back compressions
- Worms
  - Stretch/squeeze: front to back squeezing/stretching waves

Analytical Inverse Kinematics

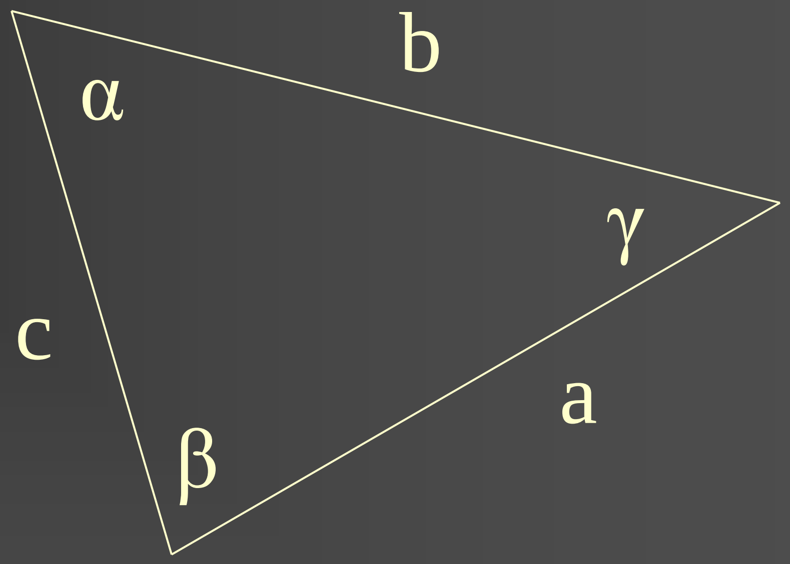
Analytical IK

- For some simple configurations, one can directly solve the inverse kinematics
- With some finesse, one can construct fairly elaborate analytical solvers even for complex configurations with redundancy
- We will just look at a simple example

Laws of Sines and Cosines

- Law of Sines:

$$\frac{a}{\sin\alpha} = \frac{b}{\sin\beta} = \frac{c}{\sin\gamma}$$

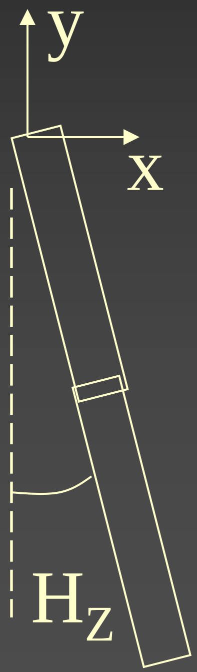


- Law of Cosines:

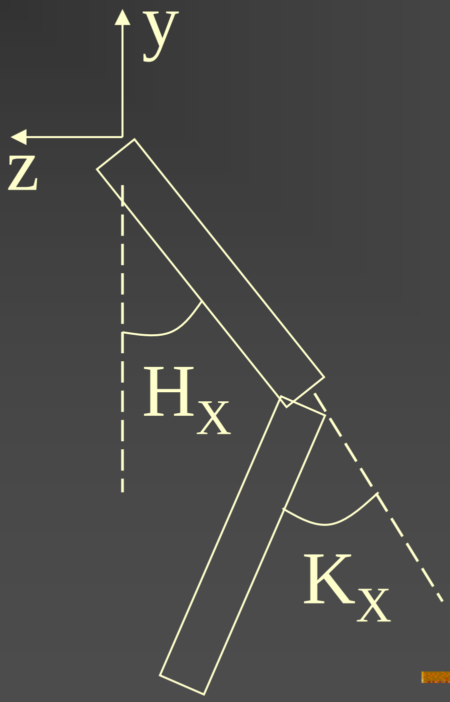
$$c^2 = a^2 + b^2 - 2ab\cos\gamma$$

3-DOF Leg

- Consider a leg with a 2-DOF (XZ) hip joint and a 1-DOF (X) knee



View from behind



View from right

Step 1: Find Unrotated Hip Matrix

- We start by computing a world matrix representing where the hip would be if it was in an unrotated state
- We make a translation matrix for the hip offset and multiply that with the parent's world matrix

$$\mathbf{H}_0 = \mathbf{W}_{parent} \cdot \mathbf{T}(\mathbf{r}) = \mathbf{W}_{parent} \cdot \begin{bmatrix} 1 & 0 & 0 & r_x \\ 0 & 1 & 0 & r_y \\ 0 & 0 & 1 & r_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Step 2: Transform Goal to Hip Space

- We want to transform the IK goal position relative to the unrotated hip space
- From this point on, we can solve the problem in this space

$$\mathbf{g} = \mathbf{H}_0^{-1} \cdot \mathbf{g}_{world}$$

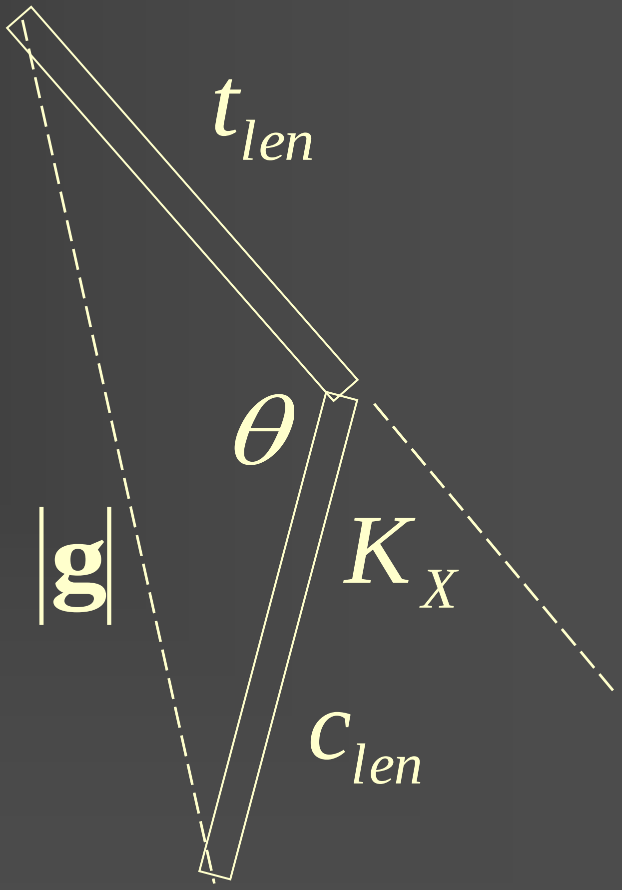
Step 3: Find Knee Angle

- We will use the law of cosines to help us find the knee angle
- The length of the thigh & calf are assumed to be constant. They make up two sides of a triangle
- The third side of the triangle is made by the distance from the hip to the goal. As the hip pivot is located at [0 0 0] in hip space, we just take the distance to be the magnitude of **g**

Step 3: Find Knee Angle

$$\theta = \cos^{-1}\left(\frac{t_{len}^2 + c_{len}^2 - |\mathbf{g}|^2}{2t_{len}c_{len}}\right)$$

$$K_X = \theta - \pi$$



Step 4: Find Hip X Angle

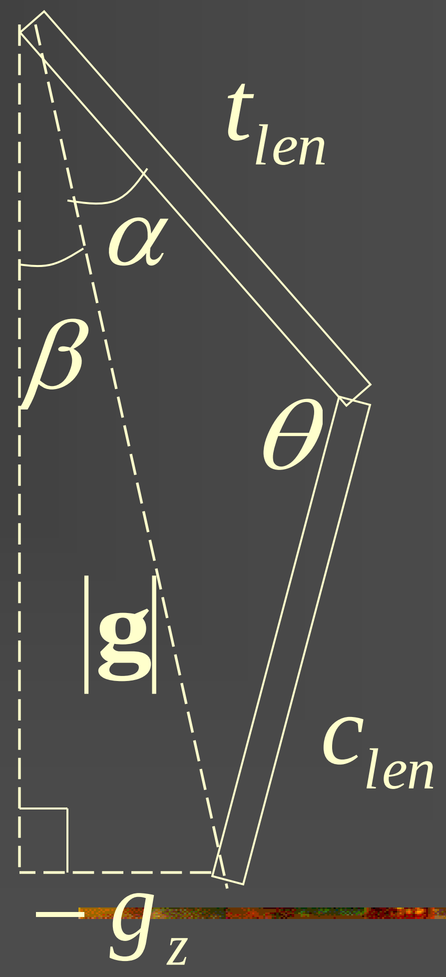
- We find the hip X rotation by continuing with our triangle analysis
- We find the upper angle α in the triangle using the law of sines and then add that to the angle β to the goal
- Note: we are looking at the problem in the plane of the in the leg's bend (the plane normal to the knee rotation axis)

Step 4: Find Hip X Angle

$$\alpha = \sin^{-1}\left(\frac{c_{len} \sin\theta}{|\mathbf{g}|}\right)$$

$$\beta = \sin^{-1}\left(\frac{-g_z}{|\mathbf{g}|}\right)$$

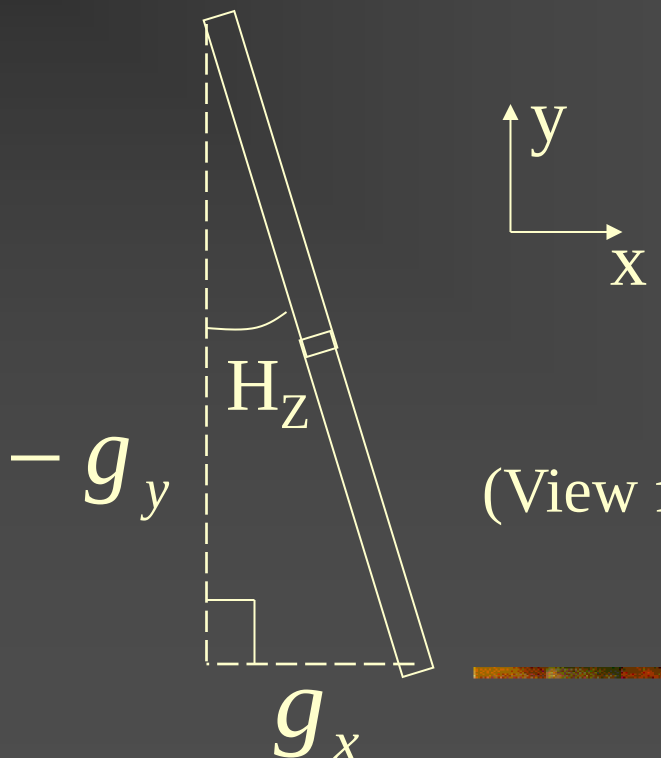
$$H_X = \alpha + \beta$$



Step 5: Find Hip Z Angle

- We find the hip z angle by looking at the goal position (in hip space) in the XY plane

$$H_Z = \tan^{-1}\left(\frac{g_x}{-g_y}\right)$$



(View from behind)

Analytical IK

- Actually, the process is a little more complicated, as some of the equations may result in divide by zero’s, square roots of negative numbers, or inverse trig functions with parameters outside of the legal range
- These cases indicate situations where there is no solution and may imply problems such as:
  - Goal out of reach (further than $t_{len}+c_{len}$)
  - Goal too close (closer than $|t_{len}-c_{len}|$)
- These cases should be checked and appropriate alternative solutions need to be designed to handle them

Bibliography

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