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Out on a Limb
Limbs do wonderful things. They simultaneously hint at ancient shared ancestry while revealing their possessors' lifestyles. Sometimes the fossil record tells such stories, but so can an artist's eye trained to look for homologies among zoo animals. Is a giraffe more closely related to a warty pig or a zebra? What on earth is a whippomorph? Participants in "Out on a Limb" learn simple, rapid sketching techniques, then apply these skills in order to compare limbs, joint-by-joint from torso to toe, among several animals that can be visited at the Oregon Zoo.

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OUT ON A LIMB

Sketching Bone by Bone from Joint to Joint at the Zoo

And she sang the low, crooning seal song that all the mother seals sing to their babies:
You mustn't swim till you're six weeks old,
Or your head will be sunk by your heels;
And summer gales and Killer Whales
Are bad for baby seals.
Are bad for baby seals, dear rat,
As bad as bad can be;
But splash and grow strong,
And you can't be wrong.
Child of the Open Sea!

Rudyard Kipling, "The White Seal"

Readers of Kipling's lovely poem may find themselves taken aback by the idea of seal heels. Most often a seal's forelimbs are described as "flippers." Its hind limbs—in effect, a second pair of flippers looking much like a tail—do have what might be called heels. Swimming with flippers is something baby seals need to learn lest they fall victim to an ocean predator, the killer whale.

An arms and legs race has unfolded between predator and prey ever since the lobe-fins wiggled ashore to become tetrapods. Some returned to the seas: the flippered and the fluked, the white seal and the killer whale. From pinniped to pachyderm, limbs differ dramatically in order to accomplish crucial functions, and zoos are well suited to the study of this diversity. Creatures held captive in zoos or animated with exaggeration in cartoons can get close looks, affording an investigator the opportunity to figure out whether, for example, elephants have knees or seals have heels—and maybe even hips. The trick is to draw them.[1]

Knowledge of comparative anatomy, especially limb structure, served cartoon animator Chuck Jones very well. Jones, creator of Bugs Bunny, Daffy Duck, Wile E. Coyote, and many other familiar Looney Tunes characters, perfected both form and movement in his animations. Jones clearly anthropomorphized the faces of his creations, but he also maintained accurate limb proportions and kept limb joints in their proper configurations. A powerful hop in an unanticipated direction is a good way to escape from a predator. Bugs Bunny, to the consternation of Elmer Fudd, embellishes his escapes with numerous tricks—but he still runs on proper bunny feet. The speedy Roadrunner, abetted by similar trickster stunts, forever seems to frustrate Wile E. Coyote, but likewise does so on bird limbs that are scientifically accurate.

In his autobiography, *Chuck Amuck*, Jones recounted the story of animating Rudyard Kipling's tale "The White Seal" as a Disney production. Let's forgive for a moment the animator's failure to distinguish between seal and sea lion. What the Disney people expected was animation that captured pinniped swimming (seals, sea lions, and walruses) in a convincing manner.

Sea lions do have several traits that distinguish them from seals: small external ears, for example. Sea lion swimming parallels seal swimming, however, because both animals utilize similarly structured flippered or "finned" feet, modified appendages descended from their land-living forebears.

Pinniped Grandchildren

Jones understood the relationship between structure and function. He realized that "all animals move the way they must move, because their unique anatomy develops as necessary in each unique environment, and the sea lion is no exception." To improve his animation, Jones went to the San Diego Zoo, where he studiously watched sea lions:

> I could not conduct a course in comparative anatomy with my animators. I was not educationally equipped to do so; therefore, I followed the most logical substitute—comparing my own anatomy to that of the sea lion. This is not as difficult as it might sound, since all vertebrates have more structural matters in common than differences. Our bones and muscles all bear pretty much the same names and are readily identifiable; the great differences are primarily in length and weight of the bones and the musculature, and, of course, in the skull structure.[2]

He observed that onshore, sea lions moved with a "complacent wobble" similar to the way "movie moguls actually walked." Once in the water, everything changed: "The sea lion becomes a sinuous master of the aquatic arabesque, a series of graceful notes swirling through the water with confident beauty."[3] Jones concluded that the sea lion's flippers were hands and feet, not fins, because they had obvious toenails and fingernails. He guessed that the upper arm bone (humerus) remained within the body. Only the lower arm (radius and ulna plus wrist and hand) from the elbow joint outward emerged. How did Jones test this hypothesis without conducting a sea lion dissection?

Back at home and away from the zoo, he recruited his two grandsons, ages eleven and thirteen. Next he tied their arms to their bodies down to the elbow and tied their legs together from hip to ankle. He helped them don swim fins on both their hands and their feet. Apparently, boys with arms pinned to their bodies and legs bound together work perfectly well as analogues to pinniped mammals.

Had the seals been present, they would have looked on with amazement, bewildered at the site of boys imitating seals, but relieved that such boys might well serve as stunt doubles. Trained seals are willing to go only so far in helping with the filming of a Disney production before a stunt double has to be called in.

Jones's animator colleagues assembled as an audience, and into the pool tumbled the two highly animated grandsons. "Within minutes they were swimming the only way they *could* swim—awkwardly, but exactly as a sea lion swims." They dove in sweeping arcs, though less gracefully than true sea lions, and surfaced quickly to breathe—in a much greater hurry. "They were as close as a human being could be to a sea lion, and the awkwardness of their movement could easily be corrected by the animator."[4]

Yes, this was a looney idea. Do not try this experiment at home with your own children or grandchildren, or other people's children for that matter. In fact, it would be a bad idea to try this experiment on yourself, especially with no lifeguard on duty. The good news: the boys survived just fine, although they spent the rest of the afternoon bouncing beach balls on their noses.

Shoeing the Ankle

In *Chuck Amuck*, Jones's sketches of Elmer, Daffy, Bugs, and Porky Pig appear on the same page as his sketches of horse, human, dog, cat, and cow limbs. The caption states, "Same bones—different lengths only."[5] Jones's drawings superimpose the body forms of the cartoon characters on lines corresponding to curves, angles, and orientation of the backbone and limbs positioned for motion. Change the angle, change the length, change the character, and change the action.

In another illustration, Daffy, Bugs, Elmer, the Tasmanian Devil, and Yosemite Sam are in a police lineup. The first frame uses horizontal lines and vertical axes to establish proportions. The next frames add basic shapes, then body contours. In the last frame, Jones superimposed photos of his animator colleagues.[6] They probably chuckled when they saw the result.

Humorous, yes, but more important, Chuck Jones's cartoons teach how to invent new, strange, and silly creatures by varying the proportions, angles, and basic shapes used to draw real animals quickly. His techniques keep these creations believable as skunks, ostriches, and roosters.

With just modest practice, even novice artists may succeed in rendering realistic drawings of zoo creatures. A good training exercise in this regard is to play Nike designer to the tetrapod kingdom. The Chuck Jones challenge is to design a pair of sneakers that properly fit a horse, a kangaroo, or a sloth.[7] Recognizing how and where the joints of the foot and leg bend are essential to this task. Think length, angle, action. The trick, Jones explains, is to know which parts of the foot, ankle, and shin belong inside the sneaker and which parts do not.

On a human, basketball shoes cover the ankle. A Nike designer will want kangaroo, horse, and sloth sneakers to do the same. If a kangaroo were to play basketball while wearing the proper footgear, the shoe, as Jones realized, must tie just above the ankle. Where's the ankle (tarsal bones) on a kangaroo? It's just above the back part of the foot that touches the ground (the heel or calcaneus) when the kangaroo is at rest. That's the same manner in which the human foot touches the ground when at rest. A standard Nike basketball shoe, size one hundred, would be a good approximation of a sneaker fit for a kangaroo.

Socks look sharp when pulled up to the knee, placing the venerable swoosh in clear view. So, on which part of a kangaroo leg do you draw the sock? The kangaroo's knee joint lines up with its belly. It's going to need an extra-long pair of tube socks.

The challenge of fitting a sneaker to a three-toed sloth or a draft horse is somewhat greater. In the sloth, the joints are more subtly hidden by the blobby body, but the comparative strategy suggests, joint by joint, where to look. The sloth sneaker will most definitely require strongly reinforced toes, given its long, curling claws.

Horses, of course, have a joint that corresponds to the human knee. It joins the base of the thigh bone (femur) of its hind leg to the top of its tibia. The patella, or kneebone, caps this joint, known in equine circles as the "stifle." The ball end of the femur fits into the socket of the hip. For the most part, the femur section is at belly height and above, the knee (stifle) thus placed well above the ground. The leg bones swing at the hip, bend at the knee, and angle again at the ankle joint. The horse's ankle (its tarsals and calcaneus or "hock joint") sits rather high as well. When a horse is shod with a human shoe, the sole runs from the toe to just beneath the ankle, giving the horse sneaker an elevated sole. The horse actually perches on its toe and the single toenail at the end of each foot thickly expressed as a hoof. Maybe that's how the *Perch*eron got its name. (Actually, Perche is the name of a place in France where the Percheron originated.)[8]

Humans play basketball quite well with just one pair of shoes and naked hands. Because they have legs and not arms, horses will need two pairs. With its upper limbs free, a kangaroo might do okay on the court. Horses, however, probably cannot dribble or shoot well with their forelimbs. Still, you might wish to design front-foot sneakers for them and leave them to set picks—an awesome equine defense! Designing with analogy to humans in mind is more difficult because people do not wear shoes on their hands (except, perhaps, in silly skits at summer camp, making, quite literally, asses of themselves). To arrange a fit similar to the one for the hind limb, the forelimb shoe must enclose the knuckles (or "fetlock" on the horse) and reach to just above the horse's wrist (or "knee"), partway up the front leg.

Dog knuckles, wrists, ankles, elbows, and knees fall in between those of kangaroos and horses from the perspective of sneaker-fitting. If you are interested in turning a dog into a sea lion with swim fins instead of sneakers, it is best to start with a dachshund, urges Jones.[9] They might do better at water polo than basketball, given their height. At the very least, a comically swimming, finned dachshund will remind us of our lobe-finned ancestors.

At the Oregon Zoo, Eddie the Otter is the star basketball player.[10] He dunks with abandon. Of course, Eddie's brand of basketball is aquatic and hence his sneakers are just for show. They would get in the way of his webbed feet, needed to propel him through the water and up to the rim, dribbling water from his whiskered chin as he dunks the ball. Zookeepers have prescribed hoop-shooting as therapy for Eddie's arthritis. (When Disney decides to animate "Eddie's Hoop Dreams," the animators will be able to watch the otter on YouTube.) I imagine that Chuck Jones would have had more difficulty using his grandsons to model an otter's swimming than that of a sea lion. Otters propel themselves with large tails, which boys lack.

Elephant Knees and Giraffe Elbows

Imagine touring a zoo guided by Chuck Jones and his animator team. Enter with an artist's sketchbook in hand, asking, "How do limbs differ from creature to creature?" The task is to sketch the limbs of a variety of creatures from their shoulders and hips to the tips of their digits on the fore and hind limbs. A few exhibits may have models, sculptures, or skeletons that will help you do so. The previous chapter introduced the strangest "limbs" of all, the appendages of the lungfish in the African swamp exhibit. Crocodile limbs are quite interesting as well. (Do keep your distance unless seeking to turn your nose into a trunk while examining them—the story found in the next chapter). Crocs often remain still or move slowly, making the digits readily apparent and the angles at the joints easy to observe.

Sketching animal limbs from torso to toe tip engages zoo visitors in comparative anatomy and focuses attention on the positions of ankles, elbows, knees, and wrists. One amateur artist begins a sketch of an impala and immediately discovers "Its knees bend backward!" Another adds, "Looks to me like the stork's knee bends backward too."

Nearby, another zoo visitor looks at an elephant and wonders "Do elephants have knees?" "Yes," a friend responds. "They're right there by the belly and easy to see when the elephant walks." Anthropocentric perception prompts zoo visitors to observe that the hind legs of many creatures appear to "bend the wrong way."

At first glance, the supposed knee joint of a large quadruped mammal (especially the ungulates) or a bipedal bird may appear to bend backward. That's because its toe-perching stance and stretched-out lower bones lift the ankle joint (taken for a backward-bending knee) and place the knee high (the joint between the femur and the radius and ulna) and close to the torso. Humans grow accustomed to feet with heels on the ground. For animals that tend to stand up on their toes, the heel takes an elevated position similar to that of the human knee. It sticks out to the back like a knee that bends backward.

The long forelimb of the giraffe prompts a question analogous to the elephant knee conundrum: "Do giraffes have elbows?" In both cases the answer is yes, but convincing oneself that this is so requires tracing the bones from joint to joint, noting the angles as they flex, and placing segments of animal limbs in a sequence that corresponds with those of a human. Doing this makes good use of human-centric perception. Exhibit by exhibit, sketchers may proceed on the prowl to detect wrists, ankles, knees, elbows, heels, and toes.

The elephant's toe-standing stance may prove difficult to discern and counting its toes somewhat confusing as well because of the fatty pad in the back of the foot that provides support. Because zoos often lack exhibits of skeletons, try to check out an elephant or mammoth skeleton on your next visit to a natural history museum. A reconstructed skeleton will lack the fatty pad, of course, bringing the structure of the foot into clear view and making apparent the tippy-toe stance.

How strange to think of a kangaroo sitting back on its ankles while the bulky elephant tiptoes about.

Each elephant foot also has in the back a false sixth toe within the fatty pad. The sixth toe is a bony structure whose existence has puzzled scientists for three hundred years. As it turns out, a similar and unusual sixth toe, or "panda's thumb," serves the panda well as a means of grasping bamboo. Moles develop a sixth digit that aids in digging.[11] These sixth digits reverse the long trend of descent among tetrapods that stabilized at a count of five digits (after reaching eight in *Acanthostega*), and then continued as a frequent reduction from this number to four, three, two, or one load-bearing, grasping, or clawing digit. Front feet and hind feet may differ in the number of toes. For example, the crocodile has five on its front feet and four on its back. It is recommended not to get close enough to confirm this observation in the wild. Make this a zoo inquiry.

Performing elephants often bend down on their "front knees" (carpal bones) the same as do trained horses. Taking a bow "on bended wrist" would certainly sound peculiar. Knees can be found on the forelimbs of many four-footed animals, dogs and horses included. They have elbows higher up—in effect, "above the knee." There are therefore bones between their knees and elbows: the radius and ulna (mostly fused in the horse, these more twisty bones constitute the forearm in humans). Elephants, you see, do have knees—fore and aft.

So, what makes a knee a knee? Maybe a knee is a knee based on the geometry of how it bends. Maybe a knee is a knee because it forms the joint between the single femur and the paired radius and ulna, all capped by the patella. The answer depends on the namer: trainer or biologist. Naming is helpful to the animator, but the important task is to get the bones sequenced, proportioned, joined, and articulated correctly whatever their names.

As Chuck Jones realized, the hip of a sea lion is located near the end of the body, where the back flippers flare out. Of course, the human torso has a hip girdle at its lower end as well, but the legs put the human hip about midway between feet and head. In the sea lion, the hip and feet are in close proximity, the structure Jones achieved by binding two boys' legs together. People with legs bound can freely move only their feet, like a seal or sea lion.

A sea lion wearing trousers would need to tighten its belt just above its hip—at the waistline. Very short shorts would suit the sea lion just fine. Look closely at the flippers in order to find the fingernails. Or do you prefer to call them "flippernails"?

The zoo depends on recreational visitors, but zoo people expect to accomplish more than entertainment. Silly musings while limb-looking enhance engagement with the animals on display. Exhibit designs teach that habitat conservation is the best means of species preservation. Modern zoos are biodiversity arks that have inherited an entertainment and recreational role. This inheritance and the conservation message combine to craft visitor encounters that evoke appreciation for wildlife while aiding in the training of animators.

Zoos pay close attention to principles of artistry in crafting visitor encounters: exhibits are vivid depictions, arrangements of species cohere around themes, and multiple art forms focus attention. A charcoal sketch portrays a chimp's pensive facial expression; a bronze sculpture freezes a polar bear's efficient paddle; a series of panels isolates a penguin's displays of aggressive and submissive behaviors. Whether in verse or visual form, no exhibit is without art.

Sketchy Zoos

Sketching allows us to hold captive in the imagination the great diversity of limbed life. So distinctive are the feet and toes of hippos and storks, rhinos and bears, zebras and sea lions! Within these extreme differences deep similarities remain. The forelimbs of naked mole rats and fruit-eating bats end in fingers—clawed in one case, webbed in the other. The bone lengths vary, but the sequence of joints aligns from species to species, exactly as taught by Chuck Jones.

Pencil in hand, the amateur artist begins the zoo tour. Careful portraits of lumbering elephants and tottering penguins, posed in a series of positions, remain for now the professional animator's dream. Achieving realism, elegance, and complexity is not the goal: the line's the thing. The line segments depict angles and lengths. From shoulder to toe the segments zig then zag, some short, some long. The back may arch, run straight, or sag. With training, getting the proportions right becomes possible. A thumb moves along a pencil held in the line of sight; the segments marked by the thumb's position and the pencil's angle transfer to paper in correct proportion and orientation.[12]

Stick rhinos and stick hippos appear on the pages of the journal. The elephant's massive body reduces to skinny lines and angles. The necks of storks and giraffes seem almost silly in proportion to their bodies.

Trapezoids, triangles, squares, circles, ovals, and rectangles create heads, necks, limbs, haunches, shoulders, ears, muzzles, hooves, and tails. Soon a stocky mountain goat, then a bulbous Visayan warty pig, later a rotund orangutan, and eventually a long-limbed gibbon peer back from the pages.

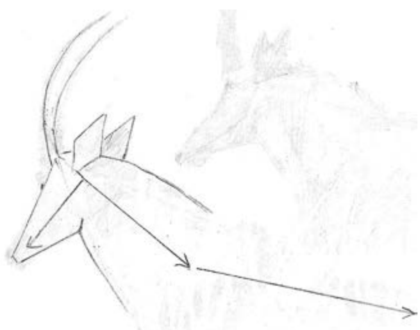


Figure 6.1 From angle to sketch of the neck and head. Illustration by Jan Glenn.

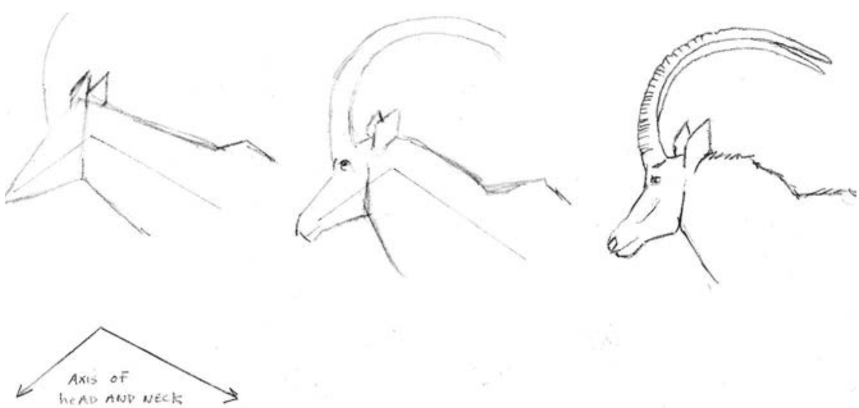


Figure 6.2 Angles, shapes, contouring, and detail in the sketch of an antelope's head. Illustration by Jan Glenn.

Two steps remain: (1) contouring the outline of the animal's profile and (2) finishing with shading. The process is Picasso in reverse: contouring the blocky impressions yields more realistic forms; then adding details of shading plus impressions of feathers or fur completes the picture. Ideally, a second sketch follows, completed in similar style yet focused on another feature of particular interest: the neck and head, with attention to dentition or feathers, for example.[13]

The ankle and elbow tour of the zoo guides attention to the proportions and shape of the body, too. By "going out on a limb" to its nailed, hoofed, padded, or clawed end, the artist hypothesizes the relative positions of knees, ankles, and elbows. Each change in angle implies a joint, shoulder to foot. The sketching mantra does the trick: make a stick figure, block in basic shapes, contour the edges, add some shading, finish with details to taste. Work quickly at each task. Be the artist you can most certainly be.

Make sure to fine-tune the digits. Do claws, hooves, or nails come in singles, doubles, triples, or more? Do they turn inward or outward or backward or align straight ahead? Which way do the hind toes point on creatures that climb: the sun bear, the margay cat, the local squirrel that chanced to run by? Note which parts of the foot or hand touch the ground when the creature walks and whether these contact points are the same or different when it stands or runs.

Attention to drawing details slows down the all-too-often frenetic tour of the zoo. You simply see more and very probably feel more. Style of movement, adaptation to habitat, and degree of common ancestry: all are bound up in limb structure. (The same could be said of skulls.) Awareness of the astonishing details of limbs, united by common descent and diversified by adaptation to different habitats, sows seeds of wonder.

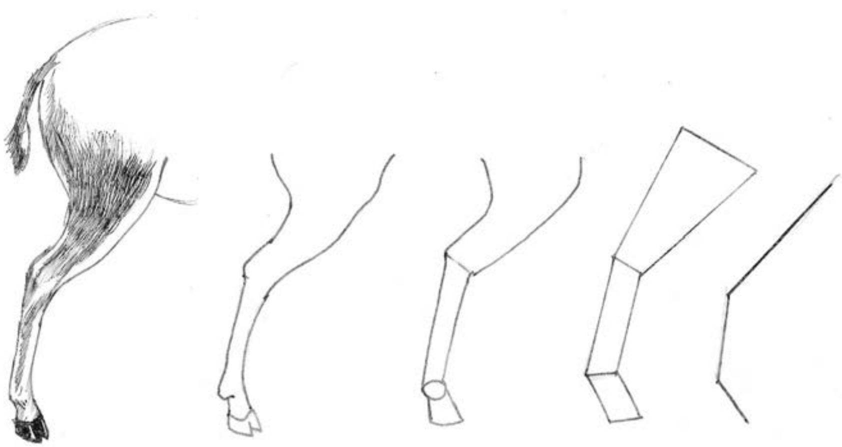


Figure 6.3 From line to limb. Illustration by Jan Glenn.

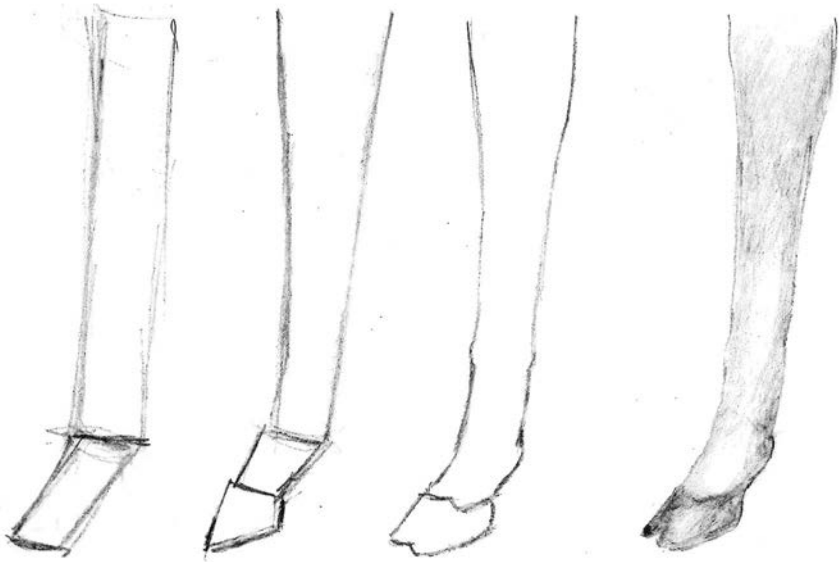


Figure 6.4 From line to hoof. Illustration by Jan Glenn.

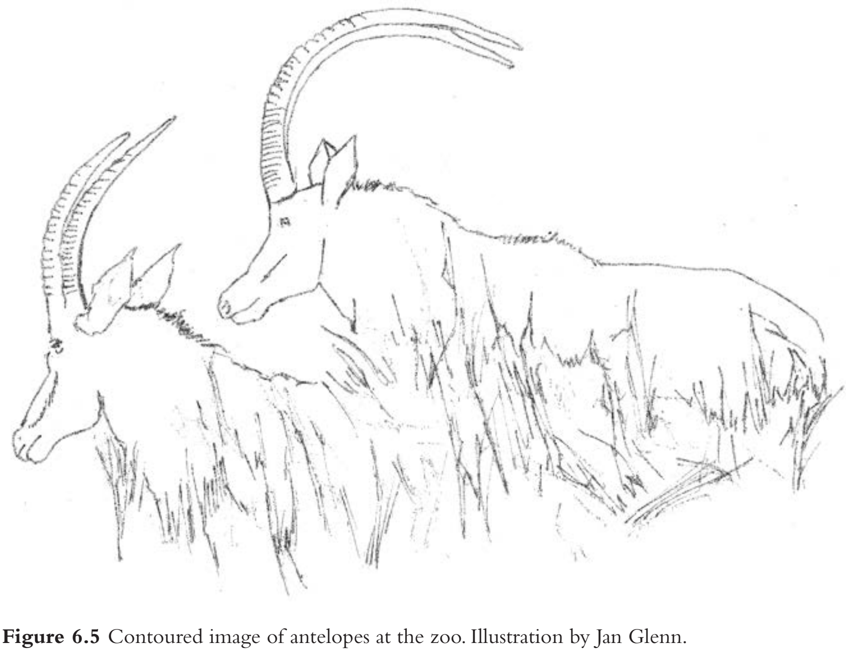


Figure 6.5 Contoured image of antelopes at the zoo. Illustration by Jan Glenn.

Figure 6.6 Shaded image of antelopes at the zoo. Illustration by Jan Glenn.

Comparing limbs by means of sketches prompts archetypal Darwinian questions: "How closely related are bears and cats, dogs and bears, and dogs and cats?" You may make some good guesses based on the data acquired by sketching. Only cats, for example, can retract their claws. Claws are always visible on bears and dogs. One trait is not definitive, but the retractable claw does suggest that dogs and bears are the closer kin, with cats more distant on their tree of common ancestry. If looking closely at the zoo creatures turns you curious about these matters, some quick Googling will map out the affinities of mustelids (weasels, ferrets, martens, polecats, stoats, and more), pinnipeds (seals, sea lions, walruses), canines (dogs and wolves), ursids (bears), and felines (cats). At the zoo tour stage, the hand trains the eye and the eye stimulates the mind.

The Importance of Limbs

Darwinian histories portray the stunning creativity of natural selection.[14] The struggle for existence through time turned lobe-finned swimmers into walkers (tetrapods), walkers into runners, and then some back into flyers and swimmers. People, not nature, decide how to parse these groups. Crossing an imaginary boundary defines evidence of the first bird, *Archaeopteryx*, or an ambulatory whale, *Ambulocetus*. Limbs feature prominently in drawing these boundaries. At some point, however, the ancestor of the first bird was not truly a bird and the earliest progenitor of the whale was not an actual whale. Nevertheless, they had limbs that changed through tens of millions of years and left telltale signatures in the joints.

For example, the story of flighty *Archaeopteryx*'s wrist bones foreshadows that of scrambling *Ambulocetus*'s ankle bones. The former, a primitive bird, and the latter, a transitional whale, mark key steps in the derivation of species dramatically different from their ancestors. In both instances, limb bones trace the path of evolution.

Among a long-standing group of terrestrial mammals, at the end of the leg and start of the foot sits a short ankle bone, rounded at both ends like a double pulley: the astragalus. This bone defines the artiodactyls: antelope, goats, pigs, cows, sheep, deer (but not horses). These are even-toed, hoofed (and quasi-hoofed), toe-perching runners. Whales may be one of their offshoots, key evidence being that *Ambulocetus* had "double pulley" astragalus bones in its ankle joints. (The ends of the bone look like small paired wheels.)

Strange cousins emerge from a commitment to the Darwinian purpose of puzzling out evolutionary ancestry. For example, hardly anyone feels surprised to learn that whales are mammals. Within the mammals, whales represent a highly specialized and modified version of artiodactyl (even-toed) ungulates, the group of mammals that typically run swiftly on their toenails. Whales are so changed from the artiodactyl pattern that such an affinity is very elusive and difficult to recognize. Apparently whales and antelopes share an ancestor that lived tens of millions of years ago. That ancient creature's progeny turned into hippos, cows, deer, pigs, goats—and whales. Whales branched off sharply in an aquatic direction, shed their hooves, and earned a label of their own: cetaceans, a term derived from the Greek word for a giant monstrous fish. Cetologists claim that before evolving fully seagoing habits, very whale-ish creatures once walked and stalked ancient shorelines. Someday, somewhere—probably in Pakistan—a group of fourth-graders may find themselves picnicking next to a set of tracks left by a walking whale.

Classifying on the basis of limb anatomy ties whales to ungulates, tetrapods to lobe-fins, and birds to dinosaurs. Inferences about origins are embedded within classification. The comparison of wrist bones helps to solve the bird origins puzzle, similarities among ankle bones the whale one. Each story, told by comparative anatomy, amends the one, then two, then many bone limb pattern observed in *Tiktaalik* from 375 million years ago. Awareness of this stunning unity hiding amidst the variation of skeletal archetypes causes strange, enlightening, titillating, and eerie feelings.

The children of *Sesame Street* learn to classify by singing, "One of these things just doesn't belong."[15] Horses trot to a different song than cows, goats, and antelopes do: the horse "just doesn't belong." The ankles and toes tell why. The horse's hoof is a single toe, an ancient odd-number pattern, the same one that typified the three-toed horses of the fossil record. The same pattern tracks rhino fossils, from extinct gracile to modern robust forms. According to limb structure, horses and rhinos are quite closely related to each other. A good name for their common ancestor would be a "rhinorse" of course.

Is a rhino more closely related to an elephant or to a zebra? In terms of limb similarities, the rhino-zebra match is striking. Are giraffes related to zebras more so or less than they are related to storks? Relating storks to giraffes appears to be a stretch. In terms of hoofness and hipness, knee jerks and ankle twists, the stork is the one that just doesn't belong. Its wing is its thing.

Paleontologist Neil Shubin recommends touring the zoo and answering such questions as a means for understanding the history of vertebrate life. Observations of shared traits, says Shubin, "can be organized and arranged like a set of Russian nested dolls." Every vertebrate creature has a head and two eyes. One subset boasts limbs, and another, smaller one speaks and walks on two legs. That's the fish-to-us progression. For Shubin, this nesting also predicts where to look in the fossil record for potential ancestors—older and older in parallel to the nestings from the innermost subset to the outer ones.[16]

As you tour the zoo and relish the delightfully diverse ways that animals climb, swim, jump, dig, hop, run, fly, grasp, paddle, and crawl; take care to sketch joints in the same relative positions, body to toe, creature by creature. Think about an elephant kneeling down on its front legs, the risky behavior trunks make unnecessary (as told by Rudyard Kipling).

Sketching focuses on limbs, segment by segment, angle by angle. That's where Chuck Jones and his animators looked closely. Zoo sketching need not extend to animating, but Jones's primary insight is telling: structure determines how animals move. Movement, after all, is essential to survival. And Jones's boss, Walt Disney, intended realistic movement for his animated *White Seal*. The chase by the killer whale had to excite the audience with convincing realism in a cartoon format. Baby seals, the little ones who must not swim until they are six weeks old—lest, as Kipling wrote, their heels sink their heads—are indeed Disney-cute. They need time to develop their flipper muscles. Flippered swimming, the pinniped way, may lack the power and grace that flukes give to whales, but it offers dramatic maneuverability. Seals can indeed snatch fish with great success.

Chuck Jones bound the hind limbs of his grandsons together, hip to ankle, and tied their forelimbs at the elbow to their bodies. Tossed into the pool with swim fins on hands and feet, the boys mimicked the swimming motions Jones's animators were to re-create. He had forced their limbs to articulate in the same relative positions he had observed among seals and sea lions. The modified structure of their limbs determined their movements. Jones's autobiography makes no mention of whether he next tossed a few goldfish into the water for his grandsons to chase. If he did, the goldfish had little to fear.

Lesson Ideas to Accompany Chapter 9 of *Do Elephants Have Knees?*

The Saga of Mooshmael

Reflection: Mooshmael's Inheritance

Mooshmael's voyage on the *Artiodactyl* introduced the story of his inheritance shared with Doris. The story depends upon humor and whimsy to suggest the basis for arguing the surprising evolutionary affinity between whales and limbed creatures. Which images in the story are easiest to remember? In what ways do they help to make the evolution of whales make sense? What features are crucial to establishing relationships among ancestral whales and to living mammals?

Mooshmael seems to have quite a diverse set of relatives. In what sense do they represent forms that are intermediate between land (or edge of the sea) and ocean creatures?

Perhaps the most striking difference between moose (and the hoofed stock closely related to moose) and whales is what they eat. Moose munch plants; whales ingest animals (fish, squid, shrimp—snagged by teeth and ensnared by baleen). That switch is as remarkable as the change from hindlimbs to flattened tail flukes (flukes are *not* modified limbs, by the way) and from forelimbs into flippers (flippers *are* modified forelimbs). Oily skull chambers, unusual ears, and blowholes truly disguise a whale's inner moose (or hippo or *Ambulocetus*). What does the story make you wonder about? What would you like to know more about?

Imagine you could interview each of Mooshmael's aunts, uncles, and cousins about their lives. What would you ask each one?

In Bernard Wiseman's *Morris the Moose*, the cow explains that she is a cow because her mother was a cow. Morris cogently reasons that a cow's mother must be a moose because the daughter, in his mind, is a moose. Is one or the other being more logical? How would you resolve this conundrum?

Mooshmael applies this same style of reasoning across multiple generations. If your ancestors were moose, then you (Doris), their direct descendent are a moose. Mooshmael seems to have carried Morris' logic too far. At some point modifications of body and limb (and tail, skull, organs, blubber, ears, and teeth) generated such novelty that a new life form came into being: whales. Where does one draw the line between non-whales and first whales? Is the line real or imaginary? Who's to say? Is it quite true or simply whimsical to claim that whales once *walked* the earth?

Is a whale a fish? Herman Melville defined a whale "a spouting fish with a horizontal tale."

Discussion: Moose Logic

"Moose Logic" sets up an analogy between the Morris the Moose's reasoning and the classification of creatures ancestral to whales. Is a moose is a deer with a bulbous snout, or is a deer is a moose with a skinny snout? Both have snouts and antlers, features likely shared with a common ancestor. On the other hand, horses and moose both have bulbous snouts. In that respect, they both differ from deer. Maybe a horse is a kind of moose without antlers and a moose is horse unable to whinny.

From Morris' perspective, what makes a moose a moose? In other words, what features define a moose? Must a moose have all of these features, at least some of these features, or most of them? Is there a single feature that all moose must possess? What are some characteristics of moose that just happen to be but are not special to moose?

Just as the set of features that define a group of animals varies, so, too, may each feature vary. When is an antler no longer an antler? What makes a horn a horn and not an antler? Which one tends to grow in a spiral shape, a horn or an antler? Which one might you see covered in skin and fur ("velvet") and which one is made of keratin, the same material found in fingernails and hooves?

Exercise: Creature Features and Ancestry Trees

Horse, deer, cow, moose: which two are most similar to each other—more similar to each other than either is to the other two animals? Sorting out relationships as indicators of shared ancestry can be challenging, but also a playful exercise. Try to imagine recent and distant common ancestors. "Moose logic" helps to do so.

Part I: Nesting Groups with Loops

Start solving the puzzle of common ancestry by writing the names of the pair creatures (or perhaps a triplet of creatures) imagined to be most similar to each other based on an essential feature (or small number of features). Draw a loop around them. Next to this shape, write the name of one (or perhaps another pair) of few remaining animals. This one (or small group of two or three) is the most similar to the first pair in some important way. What features does it share with the first group? What feature or features does it lack?

Draw another loop around the new set. Now, in line with the two looped groups, add the name of the next and perhaps very different creature. Draw a third loop that encloses all of them. Listing and looping can go on and on. It's best to practice with a small number. Do additional creatures belong in the existing loops or require new ones? New loops can be nested within existing ones or placed next to them. For example, add a rhino. Rhinos have horns, but not on the side of the head. They do not walk on two toes, as do cows, deer, and moose. Where do they belong, according to "moose logic"?

It's OK to disagree about which features to use in arranging groups. The goal is to be logical in sorting and then use the sorting to make guesses about recent and distant ancestry. Deciding which features work best for this exercise depends upon knowledge of anatomy, inheritance, and genetics. Start the task at any level of understanding—then revise solutions based on new knowledge. Think about the thinking—and additional information—helpful to improving the solution to the puzzle.

Grouping and looping complete part one of the exercise. The outcome is a set of nested categories. The second task is to imagine ancestors shared and not shared by the members of these categories and represent them in a branching tree diagram.

Part II: Imagining Ancestry Trees

Imagine an ancestor held in common by both animals in the first pair circled. Call this creature a "Floomp." Now imagine a creature that shares a feature (or features) with the first pair and the next-most similar animal. Call this creature a "Blorf." Finally, imagine a creature that has the feature (or features) shared by all. Call this one a "Dirgot." If solving the puzzle requires inventing a couple more silly creature categories, that's fine. Feel free to redo any part of the puzzle (groupings, branchings, namings) at any stage.

The solution tree is not a fact: the solution is a plausible story of descent. The facts are the presence or absence of key features among creatures. Of course, since even features vary, there always remains room for interpretation and revision. Enjoy the challenge and be comfortable with multiple, competing answers!

The goal in part two of this exercise is to make a branching diagram suggesting the possible descent of deer, cows, moose, horses, and maybe even rhinos. Draw this branching diagram below the names arranged in a row and nested in loops. The diagram begins well below the list of creatures and starts with Dirgots. One branch extends from Dirgots to Blorfs. Another branch extends from Dirgots to the creature (or creatures) not included among the Blorfs.

Two branches extend from Blorfs. One connects to Floomps, the other to the creatures grouped in the next-to-outermost circle. That is, to the group of Floomps plus the other animals with legs (horses in the example). Floomps then branches to the two innermost creatures sorted by head adornment.

There are usually different ways to draw such diagrams. How they branch depends upon which features are considered the most important ones inherited from a common ancestor. In this exercise, Floomps stand for the most recent common ancestor, Blorfs for a more distant one, and Dirgots for the most ancient ancestor of all. Dirgots share something quite important with all of the subsequent groups. Floomps share something in common with their descendants. Sometimes, a cluster of traits, not a single feature, guides making branching decisions. The finished diagram is a "tree" of likely ancestry. It suggests what kinds of creatures might have existed in the past given the variation observed among a set of animals in the present.

Finding a "primitive" creature—one thought to be a likely precursor to later ones with similar features in modified form—sets drawing the tree forward in time rather than working backwards. Puzzling out whale ancestry works in both directions: backwards from living creatures increasingly dissimilar from each other and forward from fossils having traits suggestive of ancestor status.

Mooshmael thought about his ancestors and relatives in both senses. His family photo album held images of fossil whales and protowhales and he carried on a conversation with Doris, a living whale, about features shared by limbed-“whales” and close relatives of moose (even-toed ungulates, hippos). The cast of ancestral characters included t Uncle Basil (a *Bailosaurus*), Aunt Rodhi (a *Rodhocetus*), Cousin Amble (an *Ambulocetus*), Great Uncle Pakky (a *Pakicetus*), Great Antie Indo (an *Indohyus*). Doris counted Helene, a toothless baleen whale, among her living relatives.

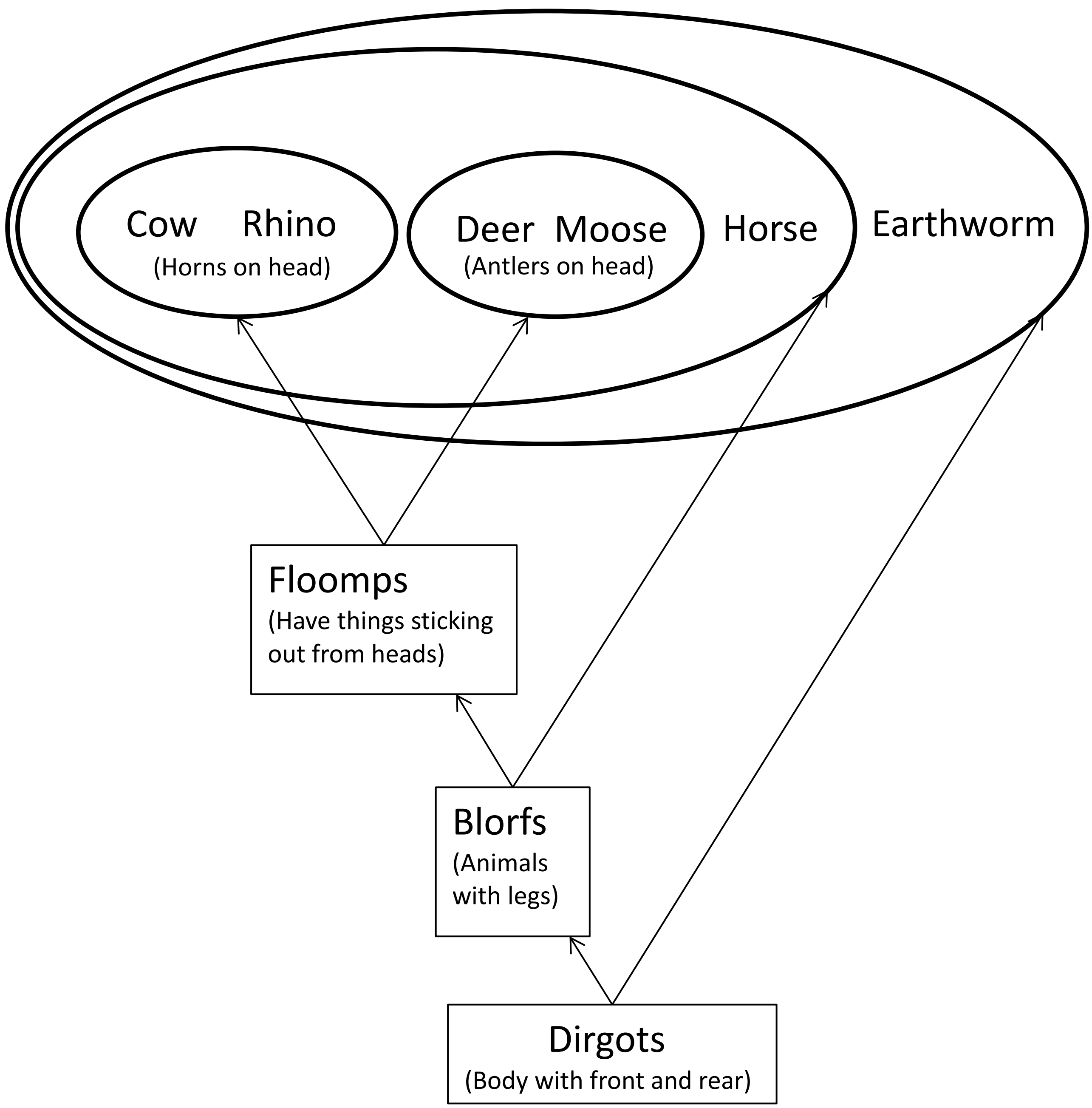
All of these creatures (with one caveat) sported enameled teeth. Baleen whales develop then reabsorb enameled teeth early in life. (Chapter 9 describes the fossil baleen whale, *Aitiocetus weltonni*, an intermediate between toothed and baleen whales). Hindlimbs disappear in modern whales, but Uncle Basil had tiny ones. Aunt Rodhi swam, but hat powerful hindlimbs—and an ankle bone very similar to one always present in living and fossil even-toed ungulates, the Artiodactyls (after whom Mooshmael named his ship). Neither Basil nor Rodhi had a fluke like Doris and Helene.

Cousin Amble had a hoof-like toe. In a very real sense, the more ancient the whale ancestor the more moose-like the limbs. Building a tree of ancestry uniting hoofed stock with fluked creatures switches from limbs to teeth at one point and to skull and ear structures at another in the work of professional paleontologists. In Mooshmael’s story, “high crowned premolars” clinches the inference of close relationship between modern Doris and ancient aunt Indo.

The adventurous might wish to draw ancestry trees suggesting the degree of shared inheritance among hoofed creatures and cetaceans, modern and fossil. Work as before: arrange the names in a row, first with a pair (or very small set) quite similar to each other—each more similar to the others in this first set than any is to any other creatures under consideration. Keep on grouping and looping with the sorting criteria explicitly in mind. Using more than one criterion at a time is certainly permissible. Don’t be too shy to look up anatomical information on-line in *Wikipedia* to resolve confusing branching points. And remember, the goal is a plausible solution to the puzzle of descent with modification—a solution that is logically consistent and grounded in an interpretation of anatomical evidence. Debating which tree best fits what’s known at present makes the science real.

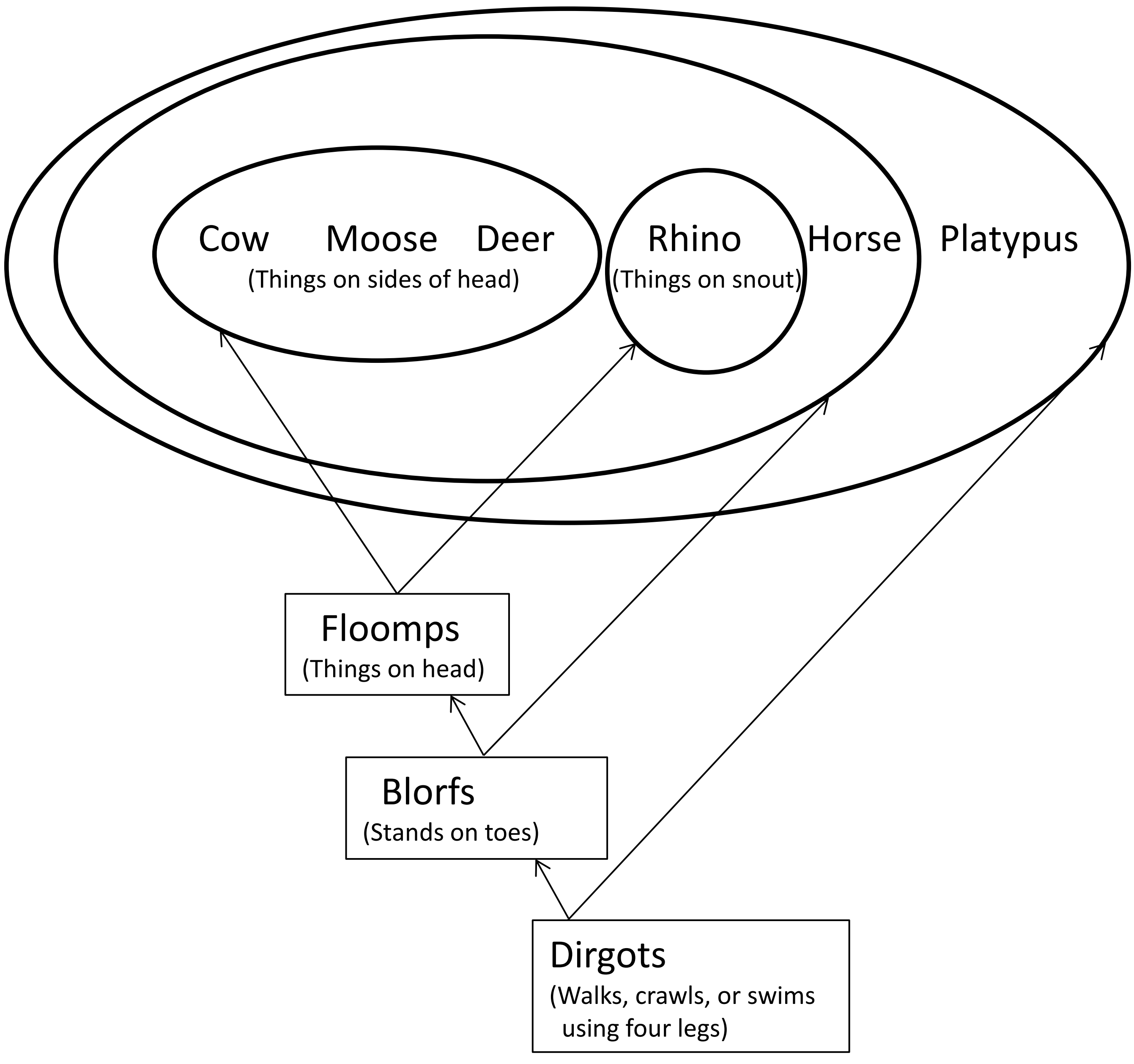
The examples are what to expect from novices—not experts. They may be “technically wrong” in some respects, but they are “intelligently wrong” in most.

Below are two examples of plausible trees of common ancestry based on the presence of obviously shared features. “Earthworms” are not Blorfs, but Blorfs and earthworms have bodies with front and rear ends. Quite likely, front-to-rear body style preceded limbs and head adornments. Heads before horns! All of these creatures qualify as Dirgots. The arrows branching from Floomps end at the horns-on-head and antlers-on-head groups. Both groups are Floomps.



This second tree shows another equally logical and equally valid (given the criteria and information at hand) solution to the puzzle. It gives priority to the feature of head adornments. If standing on two toes is judged to be more fundamental, then rhinos and horses belong in a closely related group (the odd-toe standers) as do cows, moose, and deer (the even-toe standers). That approach would yield a third, and equally valid, solution. This tree, however, only distinguishes "toe-standers."

Knowledge of "stomachs" has not been utilized in constructing either tree. It could have—stomach chambers vary from one group of mammals to another. For example, moose ruminate and have antlers; cows ruminate and have horns; horses do not ruminate and have no head ornaments. Features of skulls, limbs, digestion, limbs, and organs—and, of course, DNA sequences—combine to find the most likely tree structures.



Lesson Ideas to Accompany Chapter 11 of *Do Elephants Have Knees?*

Archaic Chickengators

Reflection: Swimming Chickens

The frog friends Jessica, Marilyn, and August mistook a pebble for chicken egg. They watched it hatch into a baby chicken that promptly took to the water. The egg had been laid by an alligator, not a chicken, of course. The fanciful story introduces major divides among land vertebrates and excuses the frog friends' misconception as a natural state of affairs. To an amphibian, chickens and gators are equally good archosaurs. What very basic traits distinguish archosaurs from amphibians? What do they have in common that may have misled the frogs?

What images in the story best help to reconstruct ideas of descent from archosaur ancestors?

Do you think a part bird, part croc creature once existed?

Discussion: Archosaur Progeny

"Archaic Chickengators" visits Triassic time in order to introduce a diverse group of early reptilian forms, the archosaurs. Archosaurs have never achieved the notoriety in the popular imagination held by dinosaurs. However, the recent reconstruction of *Canufex carolinensis*, a croc that could walk on its hind limbs, has boosted the public awareness of this over-looked group. The great Permian extinctions that preceded Triassic time left the earth's habitats open to newly evolving creatures. Archosaurs diversified into descendants well known in the present and famously extinct at the end of Cretaceous time (approximately 65 million years ago).

What groups of creatures supposedly descended from archosaur stock? Which characteristics unite them (feel free to search on-line to answer)? What fundamental differences divide them?

Many paleontologists argue that birds are avian dinosaurs. Others hold reservations and question just how and when birds became recognizable as a group whose progeny have survived quite well into the present. Do you think birds branched from archosaurs independently of the lineage that produced dinosaurs? Or do you agree with the dominant view that birds are very specialized dinosaurs—feathered raptors. What interpretation would Jessica, Marilyn, and likely argue?

What makes a bird a bird? Why are the answers to questions about the origins of birds difficult to answer? Birds are similar to, yet different from, reptilian groups. How different and in what ways must they be to no longer belong in the reptile, archosaur or dinosaur, categories?

Exercise: Table of Traits

"Archaic Chickengators" introduces difficult problems of judgment and interpretation in classifying vertebrates both living an extinct. A fossil might clearly exhibit "early bird-like characteristics" and retain "many dinosaurian features." Is it a bird or not? Flightless birds exist. Adult bird beaks are toothless. Bird bones are hollow. At some point, descent with modification reaches the point where, from a human point of view (if not a frog one), something quite distinct has come into existence that did not exist before: the novelty (and beauty) of birds, for example. They are no longer simply an example of crocodile diversity. On what basis are such judgments made?

Below is an unfinished table. Across the top are listed a set of inheritable traits. Down the side are listed a number of creatures arranged in chronological order from the present to the Triassic past. Based on information gleaned from "Archaic Chickengators" or obtained from other sources, try to complete the table. Then look for patterns through time and across creatures. What emerges as a likely scenario of descent—of trends and changes through time? What creatures appear most similar? Which ones share the fewest traits?

Creatures are listed by genus. Presumably, at this level of classification all members of the group will share the same traits. In other words, for the purpose of completing the table and inspecting it for trends or relationships, one chicken is as good as any other (of course, chickens do vary from one to another).

This is a smalltable composed of creatures mentioned in "Archaic Archosaurs." Feel free to add others as well as additional traits. For example, the thecodonts, a primitive group of archosaurs, had "socketed teeth," a useful trait for tearing apart meat.

Exercise: Evolutionary Branching (Phylogenetic Relations)

The Table of Traits displays information useful for inferring relative common ancestry and evolutionary descent. At the simplest level, counting traits contributes to making such inferences. The more traits in common the more likely creatures share a common ancestor more recently in time than they do with other creatures having fewer shared traits. All creatures ultimately share a very ancient common ancestry.

Sometimes the traits used to infer ancestry are "homologous." "Homology" refers to similar skeletal, physiological, or genetic patterns presumed to be inherited but modified during the course of descent from a common ancestor. Limb bones of similar structure and in the same relative positions in a body are homologous. Thus limbs are clues to the degree of shared (or relative recency) of common ancestry. DNA homologies are powerful tools for determining the evolutionary affinities of living organisms. Among fossils,however, DNA is rare and homologies among hard body parts are analyzed to make evolutionary inferences.

Although the Table of Traits does not track homologies, they are implicit in the skull and limb traits. The table, therefore, can be used to construct phylogentic relations. The Reference Sheet from ZEST (*Zoos for Effective Science Teaching*, NY Zoological Society, 1989) explains how to work from such a table through groupings to the construction of a branching tree diagram. The points where branches join indicate a hypothetical common ancestor. For more on constructing these phylogentic relations at a novice level consult *Dinosaurs and Their Living Relatives* (British Museum, 1985).

mya	Creature	Inheritable Traits												
		Backbone	Four Legs	Amniotic Egg	Bipedal	Scales	Feathers	Diapsid Skull	Bird-like Hips	Lizard-like Hips	Clawed Feet	Semi-lunate wrist bone	Furcula (primitive wishbone)	Pygostyle
0	*Lithobates* (Leopard Frog)													
0	*Alligator*													
0	*Gallus* (Chicken)													
68	*Tyrannosaurus* (theropod)													
110	*Deinonychus* (maniraptor)													
125	*Confusiusornis*													
150	*Archaeopteryx*													
155	*Diplodocus* (sauropod)													
251	*Carnufex* (Archosaur)													

Reference Sheet 2

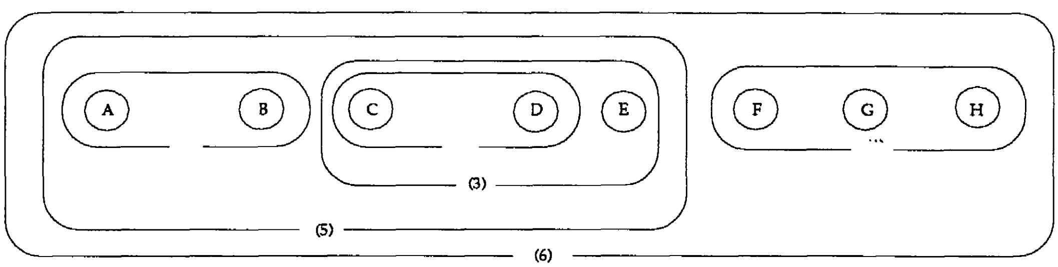
THE USE OF HOMOLOGIES TO DETERMINE PHYLOGENETIC RELATIONS

Step 1: DESCRIPTION of the distribution of homologies among various natural populations or groups of populations

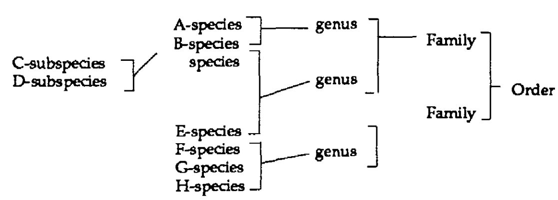
Natural populations or groups of populations	Crocodiles & Charials A	Alligators B	Snakes C	Lizards D	Tuatara E	Land Tortoises F	Freshwater Turtles G	Marine Turtles H
Homologies:								
1. 4-chambered heart	•	•						
2. Paired male hemipenes			•	•				
3. Absence of third-eyelid			•	•	•			
4. Bony shell						•	•	•
5. Elongated body	•	•	•	•	•			
6. Scales	•	•	•	•	•	•	•	•

(Hypothetical comparison of characteristics)

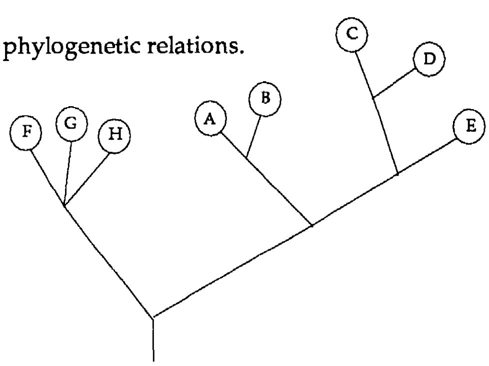
Step 2: GROUPINGS on the basis of homologous structures.



Step 3: PLACEMENT of groups into taxa.



Step 4: FORMULATION of phylogenetic relations.



Reference Sheet 1

BIRDS' FEET

The bird skeleton has evolved into a light, strong structure. Many bones have fused, as compared to its evolutionary ancestors, and are hollow instead of containing bone marrow. The typical bird leg lacks a fibula and its ankle acts similarly to the human knee (see Fig. 1). The bird femur is reduced and buried close to the body. Birds walk on the ball of their foot and toes. The leg has the ability to rotate so that the feet are always below the bird's center of gravity when walking.

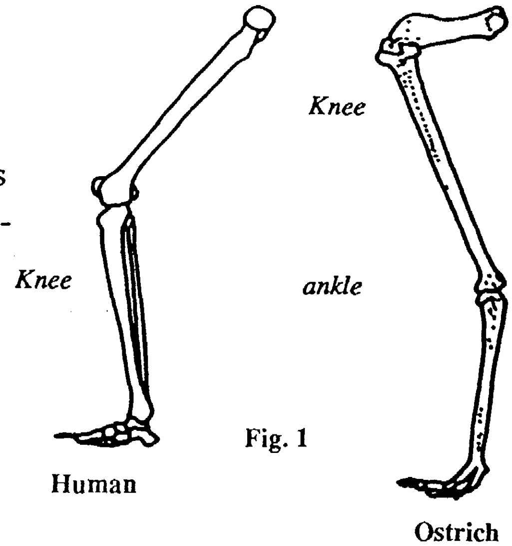


Fig. 1

Bird's feet contain from two to four toes. A four-toed arrangement may have one rear toe with three foward facing toes or two forward and two in the rear. Some birds have the ability to rotate a foward toe so that an even grasp of prey can be accomplished.

Bird feet may be used in a feeding activity such as scratching away debris; as killing tools which pierce prey with sharp talons; for perching in trees; or as locomotor organs in running, hopping, or swimming. There is often an evolutionary trade-off in foot design, as good killing or swimming feet do not adapt well to walking. Feet made for running can not also be used for killing and vice versa.

Birds of prey, such as hawks and eagles, spend much of their time soaring, looking for suitable food. They rarely walk long distances because their feet are adapted for killing and grasping their victims (see Fig. 2). The osprey foot contains four toes, each armed with a sharp talon. It uses these feet to grasp fish and has the ability to reverse one of its forward facing toes so that it can more easily carry its prey to shore.


Fig. 2 Osprey Foot

Swimming birds' feet contain structures to increase their surface area so that they act as efficient paddles. They are either webbed or lobed. The grebe has a lobed arrangement (see Fig. 3). The toes contain flaps on both sides but are not connected. When pushed against the water in a power stroke, the lobed flaps present a wide surface area. As the foot is retracted in its recovery stroke, the lobes "feather", which reduces their surface area, allowing for greater efficiency.

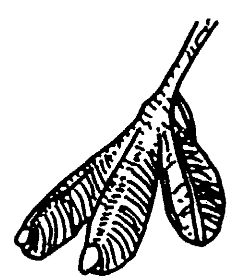


Fig. 3 Grebe Foot

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