

Eight (or Fewer) Little Piggies

Why do we and most other tetrapods have five digits on each limb?

by Stephen Jay Gould

Richard Owen, England's greatest vertebrate anatomist during Darwin's generation, developed the concept of an archetype to explicate the evident similarities that join us with frogs, flamingoes, and fishes. (An archetype is an abstract model constructed to generate the entire range of vertebrate design by simple transformation of the all-inclusive prototype.) Owen was so pleased with his conception that he even drew a picture of his archetype, engraved it upon a seal for his personal emblem, and in 1852, wrote a letter to his sister Maria, trying to explain this arcane concept in layperson's terms:

It represents the archetype, or primal pattern—what Plato would have called the "divine idea" on which the osseous frame of all vertebrate animals—i.e., all animals that have bones—has been constructed. The motto is "the one in the manifold," expressive of the unity of plan which may be traced through all the modifications of the pattern, by which it is adapted to the very habits and modes of life of fishes, reptiles, birds, beasts, and human kind.

Darwin took a much more worldly view of the concept, substituting a flesh and blood ancestor for a Platonic abstraction from the realm of ideas. Vertebrates had a unified architecture, Darwin argued, be-

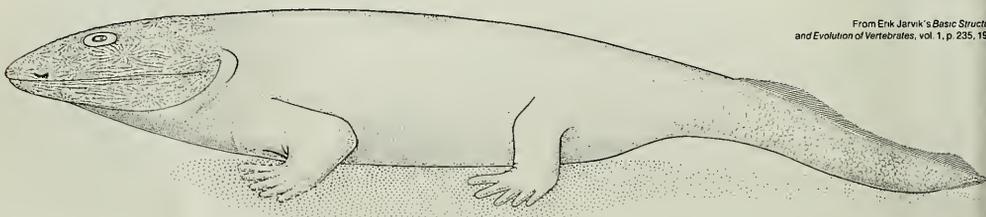
cause they all evolved from a common ancestor. The similar shapes and positions of bones record the historical happenstance of ancestral form, retained by inheritance in all later species of the lineage, not the abstract perfection of an ideal shape in God's realm of ideas. Darwin burst Owen's bubble with a marginal note in his personal copy of Owen's major work, *On the Nature of Limbs*. Darwin wrote: "I look at Owen's archetype as more than idea, as a real representation as far as the most consummate skill and loftiest generalization can represent the parent form of the Vertebrata."

However we construe the concept of an organizing principle of design for major branches of the evolutionary tree—and Darwin's version gets the modern nod over Owen's—the idea remains central to biology. Consider the subset of terrestrial vertebrates, a group technically called Tetrapoda, or four legged (and including amphibians, reptiles, birds, and mammals in conventional classifications). Some fly, some swim, and others slither. In external appearance and functional role, a whale and a hummingbird seem sufficiently disparate to warrant ultimate separation. Yet we unite them by skeletal characters common to all tetrapods, features that set our

modern concept of an archetype. Above all, the archetypal tetrapod has four limbs each with five digits—the so-called pentadactyl (or five-fingered) limb.

The archetypal concept does not require that each actual vertebrate display all canonical features, but only that uniqueness be recognized as extreme transformation of the primal form. Thus, whale may retain but the tiniest vestige of a femur, only a few millimeters in length and entirely invisible on its streamline exterior, to remind us of the ancestral hind limbs. And although a hummingbird grows only three toes on its feet, a study of embryological development marks them as digits two, three, and four of the full ancestral complement. The canonical elements are starting points and generative patterns, not universal presences.

In the tetrapod archetype, no feature has been more generally accepted than the pentadactyl limb, putative source of so many deep and transient human activities: from piano playing to touch typing, duck shooting, celebratory "high fives," and decimal counting (twice through the sequence of "this little piggy . . ."). Yet this essay will challenge the usual view of such a canonical number, while not denying its sway in our lives.



From Erik Jarvik's *Basic Structure and Evolution of Vertebrates*, vol. 1, p. 235, 1971

A reconstruction of Ichthyostega shows the early tetrapod with five digits on each limb.

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The great Swedish paleontologist Erik Jarvik closed his two-volume magnum opus on vertebrate structure and evolution with a telling point about pentadactyl limbs and human possibilities. He noted how many "advanced" mammals modify the original pattern by loss and specialization of digits: horses retain but one as a hoof; whales lose practically the whole hind limb. Jarvik noted that an essential coupling of a multidigit hand, fit for using tools, with an enlarging brain, well suited to devising new and better uses for such technology, established the basis and possibility of human evolution. If the ancestor of our lineage had lost the original flexibility of the "primitive" pentadactyl limb and evolved some modern and specialized reduction, human intelligence would never have developed. In this important sense, we are here because our ancestors retained the full archetypal complement of five and had not substituted some newfangled, but ultimately more limiting, configuration. Jarvik wrote:

The most prominent feature of man is no doubt his large and elaborate brain. However, this big brain would certainly never have arisen—and what purpose would it have served—if our arm and hand had become specialized as strongly as has, for instance, the foreleg of a horse or the wing of a bird. It is the remarkable fact that it is the primitive condition, inherited from our osteolepiform ancestors [fishes immediately ancestral to tetrapods] and retained with relatively small changes in our arm and hand, that has paved the way for the emergence of man. We can say, with some justification, that it was when the basic pattern of our five-fingered hand for some unaccountable reason was laid down in the ancestors of the osteolepiforms that the prerequisite for the origin of man and the human culture arose.

I don't dispute Jarvik's general point: the retention of primitive flexibility is often a key to evolutionary novelty and radiation. But is the five-fingered limb a constant and universal tetrapod archetype, interpreted in Darwin's evolutionary way as an ancestral pattern retained in all descendant lineages?

Erik Jarvik is maximally qualified to address this question (his rationale, of course, for raising it in the first place), for he has done by far the most extensive and important research on the earliest fossil tetrapods—the bearers and perpetrators of the five-fingered archetype in any evolutionary interpretation. (Fish fins are constructed on different principles, although the lobe-finned ancestors of tetrapods built a bony architecture easily translatable to the forelimbs and hind limbs

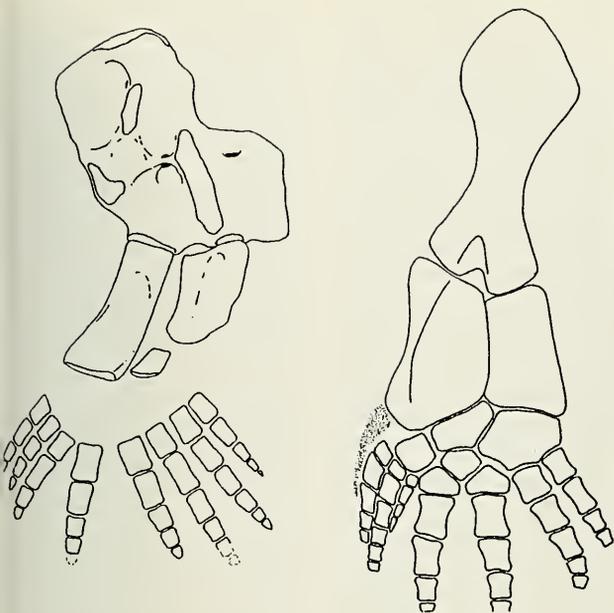
of terrestrial vertebrates. In any case, fish do not display the pentadactyl pattern, and this central feature of canonical design arises only with the evolution of the Tetrapoda.)

The oldest tetrapods were discovered in eastern Greenland by a Danish expedition in 1929. They date from the very last phase of the Devonian period, a geological interval (some 390 to 340 million years ago) often dubbed the "age of fishes" in books and museum exhibits that follow the silly chauvinism of naming time for whatever vertebrate happened to be most prominent. The Swedish paleontologist Gunnar Säve-Söderbergh collected more extensive material in 1931 and directed research until his untimely death in 1948. Erik Jarvik then took over the project and during the 1950s, published his extensive anatomical studies of two genera that share the spotlight of greatest age for tetrapods—*Ichthyostega* and *Acanthostega*. Although no specimens preserved enough of the fingers or toes for an unambiguous count, Jarvik reconstructed the earliest tetrapods with the canonical number of five digits per limb.

Our confidence in this evidence-free assumption of an initial five began to crumble in 1984, when the Soviet paleontologist O. A. Lebedev reported that the newly discovered early tetrapod *Tulerpeton*, also of latest Devonian age, bore six digits on its limbs. This find led anatomist and embryologist J. R. Hinchliffe to suggest in 1989, prophetically as we have just learned, that five digits represent a secondary stabilization, not an original state. Hinchliffe entitled his article "Reconstructing the Archetype: Evolution of the Pentadactyl Limb" and ended with these words: "Restriction to the pentadactyl form may have followed an evolutionary experimental phase."

Hinchliffe's suspicion has now been confirmed—in spades. Just last September, M. I. Coates and J. A. Clack reported on new material of *Ichthyostega* and *Acanthostega*, collected by a joint Cambridge-Copenhagen expedition to East Greenland in 1987 ("Polydactyly in the Earliest Known Tetrapod Limbs," *Nature*, September 6, 1990, pp. 66-69). Some remarkable new specimens—a complete hind limb of *Ichthyostega* and a forelimb of *Acanthostega*—permit direct counting of digits for the first time.

In an admirable convention of scientific writing that maximizes praise for past work done well and minimizes the disturbing impact of novelty, Coates and Clack write: "The proximal region [closest to the body] of the hindlimb of *Ichthyostega* corresponds closely with the published de-



From *Nature*, vol. 347, p. 67, 1990

Forelimb of *Acanthostega* (left) has eight digits. Hind limb of *Acanthostega* (right) has seven digits.

scription, but the tarsus [foot] and digits differ." In fact, the back legs of *Ichthyostega* bear, count 'em, seven toes!—with three smallish and closely bound digits corresponding to the hallux (big toe, in human terms) of ordinary five-toed tetrapods. *Acanthostega* departs even more strongly from a model supposedly common to all; its forelimb bears eight digits in broad arch of increasing and then decreasing size.

The conclusion seems inescapable, and an old "certainty" must be starkly reversed. Only three Devonian tetrapods are known. None has five toes. They bear, respectively, six, seven, and eight digits on their preserved limbs. Five is not a canonical, or archetypal, number of digits for tetrapods—at least not in the primary sense of "present from the beginning." At best (for fans of pentadactyly), five is a later stabilization, not an initial condition.

Moreover, in the light of this new information, an old fact may cast further doubt on the primacy of five. The naïve ladder of life" view depicts vertebrate evolution as a linearly ascending series of amphibian-reptile-mammal-human with birds as the only acknowledged ranch). But ladders are culturally com-

forting fictions, and copious branching is the true stuff of evolution. Tetrapods had a common ancestor to be sure, but modern amphibians (frogs and salamanders) represent the termini of a large branch, not the inception of a series. Moreover, no fossil amphibian seems clearly ancestral to the lineage of fully terrestrial vertebrates (reptiles, birds, and mammals), called Amniota, to honor the "amniote" egg (with hard covering and "internal pond"), the evolutionary invention that allowed, in our usual metaphors, "complete conquest of the land" or "true liberation from water." (The point is tangential to this essay, but do pause for a moment and consider the biases inherent in such common "descriptions." Why is the ability to lay eggs on land a "liberation"; why is water tantamount to slavery? Why is exclusive dwelling a "conquest"? Who is fighting for what? Such language only makes sense if life is struggling upward toward a human pinnacle—the silliest and most self-centered view of evolution that I can imagine.)

The first reptile fossils are just about as old as the first amphibians in the group that eventually yielded our modern frogs and salamanders. Thus, rather than a lad-



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der from amphibian to reptile, both the fossil record and the study of modern vertebrate anatomy suggest an early branching of the tetrapod trunk into two primary limbs—the Amphibia and the Amniota (reptile, bird, and mammal).

And now, the point about pentadactyly and its limits: The Amniota do, indeed, show the canonical pattern of five toes upon each limb (or some modification from this initial state). But Amphibia, both living and fossil, have five toes on the hind legs and *only four* on the front limbs. Anatomists have known this for years but have always assumed that this reduction to four proceeded from an initial and canonical five. This conclusion must now be challenged. If all the earliest tetrapods had more than five digits, and if amniotes separated from amphibians so early in the evolution of terrestrial life, why assume that the four toes of the amphibian forelimb descended from a primary five? All modern stabilizations probably proceeded from more than five. Perhaps the amphibian forelimb went from this higher number directly to four, without any pentadactyl stage between. If so, then pentadactyly crumbles on two grounds: (1) It does not represent the original state of tetrapods (as six-, seven-, and eight-toed earliest forms show); and (2) it may not mark the canonical state in one of the two great living lineages of tetrapods.

A key to understanding these new views may be found in a brilliant paper on the embryological development of limbs, based on work done just down the hall from my office and published in 1986 by Neil H. Shubin (now at the University of Pennsylvania) and Pere Alberch (now director of the Natural History Museum in Madrid)—“A Morphogenetic Approach to the Origin and Basic Organization of the Tetrapod Limb,” in *Evolutionary Biology*, edited by M. K. Hecht, B. Wallace, and G. T. Prance, vol. 20, pp. 319-87 (New York: Plenum Press, 1986).

Shubin and Alberch try to depict the complexity of the tetrapod limb as the outcome of interactions among three basic processes of branching (making two series from one), segmentation (making more elements in a single series), and condensation (union between elements). The limb builds from the body out—shoulder to fingers, thigh to toes. The process begins with a single element extending from the trunk—humerus for the arm, femur for the leg. A branching event produces the next elements in sequence—radius and ulna for the arm, tibia and fibula for the leg. The branching (to wrist bones) sets the distinctive pattern that eventually makes fingers. This key bifurcation is

markedly asymmetrical, as one bone ceases to branch (and yields but a single row of segments as the limb continues to develop), while the other serves as a focus for all subsequent multiplication of elements, including the production of digits. Oddly enough, the bone that does not branch is the larger of the two elements—the radius of the arm and the tibia of the leg. The hand and foot are made by branching from the smaller element—the ulna of the arm and the fibula of the leg.

These basic facts have long been appreciated. Shubin and Alberch make their outstanding contribution in providing a new account of subsequent branching. The classical view holds that a central axis continues from the ulna (or fibula) and that subsequent branches project from it (much like the persistent midvein and diverging lateral veins of a leaf). In this view, the roots of the digits represent different branches. Under this model, largely unchallenged for more than 100 years, debate focused on the identity of the main axis and its position relative to the digits. T. H. Huxley, for example, argued that the main axis passed through digit three; the British vertebrate paleontologist D. M. S. Watson favored digit four; while the American W. K. Gregory advocated a position between digits one and two.

Shubin and Alberch do not deny the idea of a central axis, but they radically reorient its position. Instead of passing through a particular digit (with remaining digits branching to one side or the other), Shubin and Alberch's axis passes through the basal bones of *all* the digits in sequence, from back to front.

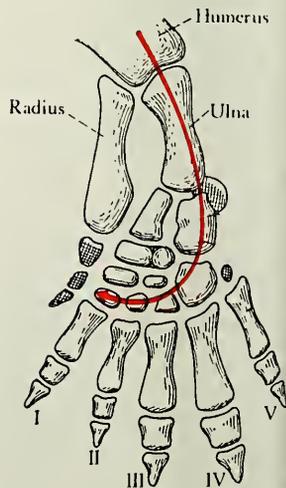
The elegant novelty of this switch may not be evident in the simple change of position for the axis. Consider, instead, the question of timing. Under the old view, one might talk about a dominant digit (focus of the central axis) and subordinate elements (products of increasingly distant branching), but no implications of timing could be drawn. Under Shubin and Alberch's revision, the array of digits becomes a sequence of timing: spatial position is a mark of temporal order. Back equals old; front is young. The piggy that cried wee, wee, wee all the way home comes first; the one that went to the market is last. The thumb and big toe may be functionally most important in humans, but they are the last to form.

(As always in natural history, nothing is quite so simple, or free from exceptions, as its cleanest and most elegant expression. Actually, the penultimate digit always forms first—ironically, the piggy that had none—and the sequence then proceeds from back to front with one exception in a

reverse branch to digit five. Moreover this generality meets a fascinating exception in the urodeles [the amphibian group of newts and salamanders, although the other major amphibian lineage of Anura the frogs, forms digits in the usual back-to-front sequence]. Uniquely among tetrapods, urodeles work from front to back [although they also follow the rule of penultimate first, beginning with digit two and then proceeding on toward five]. Some zoologists have used this basic difference to argue that urodeles form an entirely separate evolutionary line of tetrapods, perhaps even arising from a different group of fish ancestors. But most [including me] would respond that embryonic patterns are as subject to evolutionary change as adult form, and that an ancestor to the urodele lineage—for some utterly unknown and undoubtedly fascinating reason—shucked an otherwise universal system in tetrapods and developed this “backward” route to the formation of digits.)

But why bring up this innovative mode for embryological formation of digits in the context of new data on the multiplicity of fingers and toes in the earliest tetrapods? I do so (as did Coates and Clack in their original article) because the Shubin and Alberch model suggests a simple and obvious mechanism for a later stabilization of five from an initial lability that yielded varying numbers of supernu-

Adapted from Jarvik, vol. 2, p. 133



The embryological development of a tetrapod hand proceeds along Shubin and Alberch's axis (red arrow).

erary digits. If digits form from back to front in temporal order, then reduction can be readily achieved by an earlier shut-down. The principle is obvious and pervasive: stop sooner. We can reduce population growth if families halt at two children. You can cut down on smoking or drinking by setting a limit and stopping each day at the reduced number (easier said than done, but the principle is simple enough to articulate). Evolution can reduce the number of fingers by stopping the back-to-front generating machine at five. What we now call digit one (and view as the necessary limit of an invariant archetype) may only be the stabilized stopping point of a potentially extendable sequence.

This perspective makes immediate sense of some old and otherwise unexplained data of natural history. Many lineages in all tetrapod groups reduce the original complement of five to some smaller number—sometimes right down to one, as in horses. As a general principle of reduction, known since Richard Owen's time, digit one is the first to go. Owen wrote in 1849:

To sum up, then, the modifications of the digits: they never exceed five in number on each foot in any existing vertebrate animal

above the rank of Fishes. . . . The first or innermost digit, as a general rule, is the first to disappear.

Under Shubin and Alberch's model, the reason behind this rule is obvious: last formed, first gone (the natural analog of the economic maxim: last hired, first fired).

The opposite phenomenon of polydactylous mutations (producing more than five digits) also supports the Shubin and Alberch model. In humans, most polydactylous mutations produce a sixth finger as a simple duplication (subsequent to initial branching) of one member in the usual sequence of five—a phenomenon outside the scope of Shubin and Alberch's concerns. But in several other species, the supernumerary elements of multifingered mutants arise by extension as digits continue to form after the branching of digit number one, the usual terminus of the series. J. R. Hinchliffe writes in 1989: "Many polydactylous mutants . . . have an array of five normal digits, with the supernumerary digits added preaxially [that is, after formation of digit one]." Moreover, Hinchliffe cites some experimental data on inhibition of DNA synthesis during embryology of the lizard *Lacerta viridis*. With less material avail-

able for building body parts, digits may be lost. The last-formed digit, number one, is always the first to go. Data from both sides therefore support the idea that digits form in temporal series, back to front, and that spatial position is a mark of order in embryological timing: extra digits are added to, and old digits are lost from, the temporal end-point of the canonical sequence: digit number one.

The pleasure of discovery in science derives not only from the satisfaction of new explanations but also, if not more so, from fresh (and often more difficult) puzzles that the novel solutions generate. We may illustrate this theme with Shubin and Alberch's model and with our new discoveries on multiplicity of digits in the earliest tetrapods. We used to think of five digits as invariant and canonical, and our chief question was always, why five? But if five is a secondary stabilization, a stopping point in a temporal sequence with other potential (but unrealized) terminations, we must ask a very different, and in many ways more interesting, question: why stop at this point; what, if anything, is special about five?

Since five seems to possess a certain arbitrariness under the new views, the tenacity of its stabilization in tetrapods

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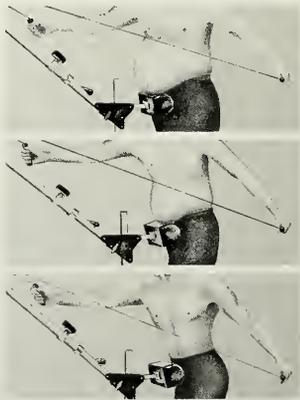
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seems all the more enigmatic. The embryological apparatus remains capable of producing more than five (at least in many species), as mutational and experimental data show. But these polydactylous mutations remain as anomalies of individuals or of small and evanescent family lines. They never stabilize within a larger group, and no vertebrate species has more than five digits generated from the back-to-front axis of the Shubin and Alberch model.

The best proof of this assertion lies in apparent (but not actual) exceptions of several tetrapod species with six functional digits. Yes, Virginia, several species do grow six fingers as a rule, not as an exceptional state of mutant individuals. Yet this sixth finger is always generated in a different manner, and not by the obvious (and apparently easy) mechanics of simple extension past digit one on the Shubin-Alberch series. Frogs, for example, often have six digits on their hind feet (or five on their normally four-fingered front feet). But this extra digit forms in a unique manner by extension of the unbranched sequence of bones leading out from the radius or tibia—the limb bones that never serve as foci for branches and therefore do not (in any other tetrapod species) participate in the production of digits. Anatomists have long recognized the anomalous character of these unique digits by naming them prepollex (for the forelimb) or prehallux (for the hind limb). (Pollex and hallux are technical names for digit number one—our thumb and big toe. Prepollex and prehallux therefore designate an anomalous digit, located in front of the usual front and formed differently.)

A few mammals also possess a functional sixth digit—the panda, whose false “thumb” has been a staple of these essays, and several species of moles. But these false thumbs are formed from extended wrist bones and are not true digits at all. These facts seem to heighten the oddity (and rigidity) of stabilization at five in a sequence that was once extendable, remains so now for mutations and experimental manipulations, but seems recalcitrant in setting a maximum of five as a normal state in all tetrapod species. When six functional digits form, the extra item must be built in another way.

So why five? Of two major approaches to this question, the conventional Darwinian, or adaptationist, strategy tries to discern a marked advantage, or even an inevitability, for five in terms of utility for an organism's mode of life (a benefit that might promote this configuration by natural selection). A plausible case can be made in terms of advantages for terrestrial life. Creatures that evolve from water

to land face many novel challenges, none more severe than the new force of gravity and the consequent need for support in the absence of buoyancy previously supplied by water. The transition from fins to limbs provides the basis for this support, and an old argument holds that five might be an optimal configuration for weight-bearing—a central axis centered on digit three, with adequate and symmetrical buttressing on each side (one or three toes might not provide enough lateral support against wobbling, while seven toes might be superfluous and interfere with locomotion). On this argument, tetrapods have five toes because support and locomotion demand (or at least strongly encourage) this configuration as optimal.

The argument is not implausible and surely gains credence from the probability that five digits evolved twice—separately, that is, in the two great divisions of tetrapods. The most obvious counterargument may also be support in disguise: why, if five is best on land, do the earliest tetrapods bear six, seven, and eight toes, respectively? A paradoxical retort holds that these first tetrapods evolved their limbs for locomotion in water and remained predominantly, if not entirely, aquatic. *Ichthyostega*, as long recognized, maintained a small tail fin and lateral-line canals on the skull. (Lateral-line organs “hear” sound by sensing vibrations propagated through water, a method that does not work in thin air.) Coates and Clack's restoration of *Ichthyostega* and *Acanthostega* limbs adds support to this interpretation in a streamlined shape and a limit to rotation that might keep the limb horizontal, in fin position, rather than rotated downward to support a body on land (at least for *Acanthostega*, although the *Ichthyostega* forelimb seems fully load bearing).

But strong elements of doubt also plague this adaptationist view. First, as stated above, members of one tetrapod lineage, the amphibians, grow but four toes on their front legs, and we have no evidence for an initial five—so pentadactyly may not be a universal stage in terrestrial vertebrates. Second, if five (with symmetry about a strong central toe) is the source of advantage, then why does our favorite species, the traditional measure of all things—namely *Homo sapiens* itself—retain five, require great strength in using but two limbs against gravity, but construct the end-member first toe as the main weight bearer? And why do the most successful of all large mammals, the “cloven-hoofed” artiodactyls, or even-toed ungulates—including cows, deer, giraffes, camels, sheep, pigs,

and their numerous allies—bear an even number of toes, with the central axis running through a space between the digits (the misnamed “cleft”)?

The second major approach—historical contingency in my favored terminology—argues that five was not meant to be, but just happens to be. Other configurations would have worked and might have evolved, but they didn't—and five works well enough. The obvious supports for this alternative view lie scattered throughout this essay. If five is so good, why do so many species devise such curious and devious means to produce six (prepollex or converted wrist bone)? If five is so predictable, why does one of two lineages grow but four? (I should say right up front that neither of these two positions—adaptation or contingency—really addresses the greatest puzzle of all: the recalcitrant stability of five once it evolves. I suspect that this is a question for embryologists and geneticists; phylogenetic history may offer little in the way of clues. Why should five, once attained by whatever route and for whatever reason, be so stubbornly intractable as an upper limit thereafter—so that any lineage again evolving six or more must do so by a different path? The inquiry could not be more important, for this issue of digits is a microcosm for the grandest question of all about the history of animal life: why, following a burst of anatomical exploration in the Cambrian explosion some 550 million years ago, have anatomies so stabilized that not a single new phylum [major new body plan has evolved since?]

But the greatest boost to contingency lies in the discovery that prompted this essay in the first place—seven digits in *Ichthyostega* and eight in *Acanthostega*. If tetrapods had five at the beginning, and always retained five thereafter, then some predictability or inevitability could legitimately be maintained. (At the very least no fuel would exist for an alternative proposal.) But if the first members of the lineage had six, seven, or eight toes, then alternative possibilities are legion, and an eventual five may be a happenstance, not a necessity.

Embryologist Jonathan Cooke, in a commentary accompanying Coates and Clack's paper, agrees with me that possible contingency of pentadactyly is the most interesting implication of the new discovery. But he makes a very curious statement in his advocacy. Cooke writes:

But for most of us, philistine enough to accept the historically contingent nature of evolution, there is nothing specially deep about the number five. Pianists should ponder the challenge that our motor cortex

would have been set had Bach or Scarlatti reported eight deeply and ineffably named fingers per hand.

I love the idea, but I decry the apology and abnegation implied by the designation of "philistine" for contingency. This unnecessary humility follows an unfortunate tradition of self-hate among scientists who deal with the complex, unrepeatable, and unpredictable events of history. We are trained to think that the "hard science" models of quantification, experimentation, and replication are inherently superior and exclusively canonical, so that any other set of techniques can only pale by comparison. But historical science proceeds by reconstructing a set of contingent events, explaining in retrospect what could not have been predicted beforehand. If the evidence be sufficient, the explanation can be as rigorous and confident as anything done in the realm of experimental science. In any case, this is the way the world works; no apologies needed.

Contingency is rich and fascinating; it embodies an exquisite tension between the power of individuals to modify history and the intelligible limits set by laws of nature. The details of individual and species' lives are not mere frills, without power to shape

the large-scale course of events, but particulars that can alter entire futures, profoundly and forever.

Consider the primary example from American history. Northern victory was not inevitable in the Civil War, for the South was not fighting a war of conquest (unwinnable given their inferiority in manpower and economic wealth), but a struggle to induce war weariness and to compel the North to recognize their boundaries. The Confederacy had almost succeeded in 1863. Its armies were deep into Pennsylvania; draft riots were about to break out in New York City. Massachusetts was arming the first regiment of free black volunteers—not from an abstract sense of racial justice, but from an urgent need for more bodies. In this context, the crucial Battle of Gettysburg occurred in early July. Robert E. Lee made a fateful error in thinking that his guns had knocked out the Union battery, and he sent his men into the nightmare of Pickett's Charge. Suppose we could rerun history and give Lee another chance. This time, armed with better intelligence perhaps, he does not blunder and prevails. In this replay, the South might win the war, and all subsequent American history becomes radically different. The actual out-

come at Gettysburg is no minor frill in an inevitable unrolling of events but a potential setting point of all later patterns.

Never apologize for an explanation that is "only" contingent and not ordained by invariant laws of nature—for contingent events have made our world and our lives. If you ever feel the slightest pull in that dubious direction, think of poor Heathcliff, who would have been spared so much agony if only he had stayed a few more minutes to eavesdrop upon the conversation of Catherine and Nelly (yes, the book wouldn't have been as good, but consider the poor man's soul). Think of Bill Buckner who would never again let Mookie Wilson's easy grounder go through his legs—if only he could have another chance. Think of the alternative descendants of *Ichthyostega*, with only four fingers on each hand. Think of arithmetic with base eight, the difficulty of playing triple fugues on the piano, and the conversion of this essay into an illegible Roman tombstone, for how could I separate words without thumbtopressing the spacebar on this typewriter.

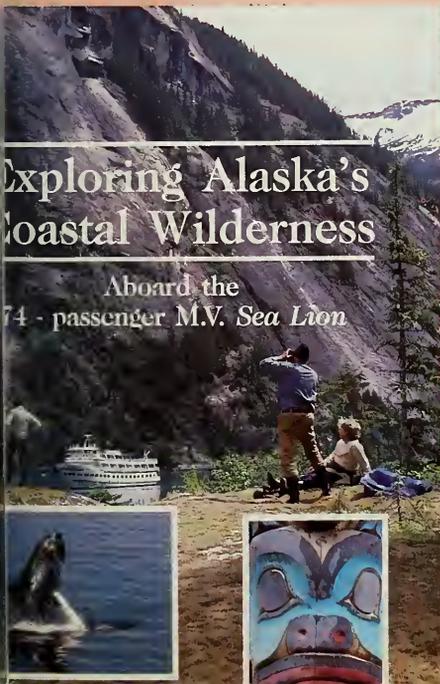
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