



AIAA 2004-0532

**Airplane Design and the Biomechanics
of Flight – A More Completely Multi-
Disciplinary Perspective**

**[Vol. 6 in a series: *The Demise of Aerospace – We Doubt
It or The Airplane Design Professor as Shepherd*]**

John H. McMasters
The Boeing Company
Seattle, Washington 98124

Russell M. Cummings
Aerospace Engineering Department
California Polytechnic State University
San Luis Obispo, CA 93407

**42nd Aerospace Sciences Meeting
5-8 January 2004
Reno, Nevada**

For permission to copy or to republish, contact the copyright owner named on the first page.
For AIAA-held copyright, write to AIAA Permissions Department,
1801 Alexander Bell Drive, Suite 500, Reston, VA, 20191-4344.

Airplane Design and the Biomechanics of Flight- A More Completely Multi-disciplinary Perspective

John H. McMasters*
The Boeing Company
Seattle, WA 98124

Russell M. Cummings**
California Polytechnic State University
San Luis Obispo, CA 93407

Abstract

Aeronautics is usually presumed to have started as a formal engineering discipline somewhere in historical time between the mythological experiments of *Daedalus* and his ill-fated son, *Icarus*; and the dreams and schemes of Leonardo da Vinci during the Italian Renaissance. As reviewed in this paper, “aeronautics” has a far longer history, extending over a period of about 300 million years beginning with the evolution of the ability of insects to fly. With the advent of the success of the Wright brothers, technologists quickly turned their attention from the inspirations and lessons provided by natural models of flying machines to a more practical quest for increasingly dramatic improvements in speed, range and altitude performance far beyond the limits of what muscles and flapping wings could provide. Based on recent work done by the first author in support of the NASA/DARPA Morphing Aircraft Structures Program, a purpose of this paper is to demonstrate in broader terms some of the numerous, very rich sources of inspiration such multi-disciplinary explorations continue to offer both the engineering practitioner and educator.

* Technical Fellow. Associate Fellow, AIAA.

** Professor, Aerospace Engineering Department.
Associate Fellow, AIAA.

Introduction

“A scientist discovers that which exists. An engineer creates that which never was.”

Theodor von Kármán

“To prove that a pig cannot fly is not to devise a machine that does so.”

Diedrich Küchemann

Advances made during recent decades in a number of unconventional areas of aeronautics (e.g. human powered flight, sailplanes and soaring, hang gliders, ornithopters) remind us that all progress during the past 100 years has not been limited to mere commercial and military applications of our technology. Indeed, a closer look at the history of our aeronautical enterprise from circa 1850 to the present shows that while not always recognized or adequately appreciated, a small band of visionaries, biologists and dedicated romantics has made extraordinary progress toward realizing one of man’s oldest dreams – to devise practical means for humans to truly fly like birds (or bats, or whatever). While the contributions these individuals have made to our art are too easily dismissed as being of no practical (i.e. military, commercial or economic) consequence, this conclusion has been extraordinarily shortsighted in the authors’ opinion.

With the recent advent of government (DARPA, NASA) interest in micro-air vehicles (μ AVs), and morphing aircraft aimed at developing concepts for aircraft capable of more-or-less radical shape change to allow them to better meet two or more divergent performance requirements (e.g. high speed dash and long

endurance), a door is finally opening to the realization that there may be *much more* to learn in further, truly multidisciplinary investigations of the biomechanics of flight as it may relate to a wide range of practical aircraft types. The present paper is intended to explore this issue in more detail and is the sixth in a series¹⁻⁶ the authors began in 2000 under what has become the general rubric: “The Demise of Aerospace – We Doubt It.”

As our original series of papers¹⁻⁴ developed, so has our agenda that now includes making a modest contribution to:

- A national need *by our aeronautics community* (industry, government and academe) to revitalize the “airplane business” by creating a positive vision of its future as vivid and compelling as that which has driven its past, as a means to...
- Attract a next generation technical workforce in aerospace that possesses a much broader “multi-disciplinary” and “systems engineering” perspective aided by ...
- Reform and enhancement of our technical education system (beginning at the elementary school level) to...
- Attract and retain a diverse student population (especially women) that reflects the shifting demographics of our society...

which is thus capable of maintaining and advancing an industry that still continues to find a multi-billion dollar a year market for its products and services, and which is fundamentally important in maintaining our security and enabling the further development of our global economy. This paper is intended to address (perhaps obliquely at times) all the issues on our agenda. A second companion paper⁵ deals with the airplane design process and means to advance this art. A third in this year’s trilogy⁶ returns to a suite of people issues that need to be addressed in order to exploit the topics discussed in the other two papers.

The Origins of Flight

As a student of, and modest participant in, the unconventional fringe of aviation over the majority of a roughly fifty-year career as an aeronautical engineer and airplane design educator, the first author on various occasions (e.g. under the auspices of the AIAA Distinguished Lecturer Program in 1992-4 and 2002-4; as an invited, but informal participant in the DARPA Morphing Aircraft Structures Program) has attempted to present the technical history of aeronautics in a much broader, multidisciplinary context than is usually done. The basic premises of the author’s lectures [now generically entitled *The Origins and Future of Flight – A Paleocological Engineering Perspective*] and earlier related writings⁷⁻⁹ include the following:

- The conventional view of aviation history (Fig. 1) is both incomplete and a bit backward. While it is now very well documented^{10, 11} that the more successful of the earlier pioneers of manned flight were inspired by and well versed in the readily observable aspects of avian aerodynamics and flight mechanics, it may be argued that in large measure we owe much of our understanding of biological (both animal and botanical) flight to experience gained, and from theoretical and experimental tools developed, in the course of designing aircraft of various types, rather than the other way around. At a minimum we should understand aviation history in the broader terms shown in Fig. 2.
- Figure 2 further suggests that rather than being separate, disconnected topics, technological and biological flight represent two portions of a continuous, very broad and fascinating spectrum – at least in connection with certain representative types of flying. A huge range of diverse devices and configurations are all tied together by the underlying requirements that each must obey the same fundamental laws of physics, chemistry – and economics as well.
- To understand the apparent differences in devices as dissimilar as dragonflies, seagulls and jet transports, one must understand not only the basic physics of flight, but also the context within which each operates. This context is spatial, temporal (covering several *hundred* million years of evolution) and

economic. Thus, as in any form of traditional airplane design problem, an “ecological” (system) perspective must be adopted.⁵ In short the aerodynamic aspects of the design problem, for example, do not exist in pristine isolation and any attempt to discuss a history of a single discipline such as applied aerodynamics, structural mechanics or flight controls must correctly include an encompassing view of the overall system to which our art contributes and by which its ideal applications are constrained.

- Further, as argued in our companion paper,⁶ ecology is the classic paradigm for a proper “system of systems” view of engineering and many other fields of inquiry. Every citizen, whether technically literate or not, experiences our global natural environment in almost all its various interactive aspects and can grasp the concept in at least outline terms. Ecology (or perhaps more specifically *paleo*-ecology to incorporate a necessary temporal component) thus offers a rich and important field of study and motivation to all students of engineering, regardless of the specific discipline in which he or she may be specializing.
- Engineers (and computer scientists), working closely with those from a range of other scientific disciplines (e.g. zoology, botany, paleontology, neuro-physiology, geology, meteorology and climatology, and particularly ecology), have much to contribute to increasing our understanding of flight in nature. The reverse of this proposition with regard to advancing aeronautical technology is also true but has yet to be adequately exploited – and should be in the future, especially as environmental concerns increasingly come to influence future technological developments.^{4,5} While this two-way process has finally and seriously begun (e.g. the models presented in the excellent current work being done by research teams led by Michael Dickinson¹² at Cal Tech and UC-Berkeley, and Tom Daniel¹³ at the University of Washington in Seattle on various aspects of insect flight and neurophysiology), far more is possible and needs to be pursued.

Biomechanics and Technology – Some Basis Lessons Learned So Far

Much of the materials for the first author’s writings and lectures over time on the biomechanics of flight came from a semi-avocational fascination with topics relating to the overlap between the spectrums of biological and technological flying devices ranging from small (microscopic) insects and pollen grains through aircraft substantially larger than the current Boeing 747. Thus attention has been drawn [cf. Fig. 2] to the equivalence between large soaring birds (condors, the albatross and extinct teratorns) and sailplanes; pterosaurs, hang gliders and ultra-light sailplanes; human-powered aircraft and all those vertebrate fliers that also have a basal metabolism rate; and at the lower end of the biomechanical spectrum to the fundamental importance of aerodynamics in the sex life of grasses and conifers (fir and pine trees, etc.) and the dispersal of aerosols and atmospheric particulate contaminants.

The benefits of these inquiries to the authors’ professional work, as educators, aerodynamicists and airplane designers, have been many, although not always obvious, and frequently considered “frivolous” or eccentric by professional colleagues even in academe. Perhaps the most important benefit has been the deep appreciation gained for the importance of *size* [e.g. Fig. 3] and hence the importance of both fluid dynamic and structural scale effects on airplane (and animal/plant) design problems. In this connection, even simple physics-based analyses within the reach mathematically of a high school student (e.g. the square-cube law, simple beam theory, the conservation laws of momentum and energy) can give insightful results as will be briefly outline later. Other topics of major practical importance that are well demonstrated in natural flying devices are advanced manufacturing techniques, the various uses of vortices for flow control, the effects and benefits of aeroelasticity and variable geometry, and (particularly in the case of insects) the problems and benefits of controlled large-scale *unsteady* separated aerodynamic flows.

In this last connection, the authors have not shared the enthusiasm of some recent investigators^{12, 14} for ornithopters (flapping wing aircraft) based largely on a strong prejudice against reciprocating machinery. It should be

noted here that with what was until recently thought to be the singular exception of certain bacteria (e.g. *E. coli*), nature has not had the benefit of the wheel as a means of aiding locomotion. Thus, birds and all other active natural fliers (as contrasted with passive gliders or parachutists in the plant and animal kingdoms) have had to rely on flapping their wings to provide propulsion. This has been thought to be “primitive” and limiting – at least with regard to the flight speeds thus achievable by such means. And so the issue has stood until recent interest in μ AVs (e.g. robotic “insects”), has forced a reevaluation of the question of whether *at the scale (size) conditions involved* (e.g. devices smaller than a large humming bird), it is in fact wiser to combine the lift and thrust generating mechanisms than to separate them. The answer may well be that the combination of functions is the better answer in this *singular* design problem, at least in part for reasons reviewed in one of the author’s earlier publications⁸. Fortunately there is now an increasing body of very good literature available^{15, 16} that allows more detailed quantitative assessments of the necessary trades to be made. Several researchers are actively pursuing the biomechanics of the problem in further detail¹² and the recent impressive experimental results published by Spedding¹⁷ shed important new light on the very complicated related problem of the flapping flight of birds.

Case Studies in the Biomechanics of Flight

The study of the biomechanics of insects is but one area among many wherein we can now see in retrospect that nature had (and still has) much to teach us regarding the possible future development of our art and our technology, or at least the basic fluid dynamic underpinning of it. Even more fruitful is the detailed study of the three lines of development of the ability to fly among the vertebrate animals (bird, bats and now extinct pterosaurs), all using wings whose load carrying structures are based on the same basic set of analogous bones to those in the human arm and hand as shown in Fig. 4. Modern birds, as one example, already fully and elegantly embody a number of items that have been the subject of much research and development in aviation in recent decades. As shown in Fig. 5 for the case of the California condor, these items include variable geometry (mission adaptive) wings of

extreme sophistication (e.g. they are capable of varying span, area, sweep, dihedral and twist; both symmetrically and asymmetrically), an advanced high-lift system, an active (“fly-by-wire”) control system, a self-repairing/self-reproducing composite structure, and fully integrated system architecture. All this offers a vast abundance of case study examples of good design (*in an integrated system sense*), possible topics for student project and thesis work; and, above all, as a stimulant to students’ imagination and creativity. Two such sample case studies of particular significance to current and future aeronautical development will be presented in the following sections and many further examples may be found in the literature cited in the bibliography section of this paper.

The Quiet, Maneuverable Flight of Owls – A Case Study



A singularly good example of nature’s complex interactive adaptations is embodied in the design of many species of owl, and will suffice to demonstrate the possibilities case studies of natural flight can provide students of airplane design. Owls are highly evolved and specially adapted to function primarily as nocturnal predators, often flying in confined spaces (e.g. within a forest) such that they need to fly slowly and with a high degree of maneuverability. They are also splendid examples of natural “stealth” technology in that their approach is not detectable by their prey (until it is usually too late), while using highly developed bi-aural direction finding (in which the ears are not located symmetrically in the skull) and night vision systems to guide them. The owl’s unique feathers (Fig. 5) aid in all this, but the specific functions of each of these special adaptations

have not been fully understood, and they turn out to be synergistic in producing the desired *system* characteristics of these highly sophisticated killers. How this works may be understood (with thanks to Geoffrey Lilley¹⁸) by considering some basic principles:

- Any object moving in a fluid generates a system of forces and noise (fluctuating pressures or sound waves of various dissonant frequencies and intensities).
- The noise generated depends theoretically on:
 - The *fifth power* of the relative speed between the flow and the object [experience with aircraft airframe noise measurements suggests that this noise component actually varies as speed to the 4.6 power].
 - The *inverse square* of the distance between the object and a receiver
 - The details of the shape and size of the object
- The aerodynamic forces on a wing (needed to fly, i.e. create *lift* to balance the animal's weight, or to maneuver) vary according to the area of the wing and the *square* of the flight speed. Everything else being equal, *doubling* the flight speed increases the forces on the wing by a factor of *four*. This works both ways. Slowing down rapidly reduces the forces produced unless other special measures are taken to increase them, e.g. fitting a wing with auxiliary high lift devices. Many birds, including owls, use their tails as "camber changing flaps" to enhance lift available from their wings, while using the ability to vary wing sweep to maintain the required relation between centers of gravity and pressure of the overall configuration.
- Since, everything else being equal, the noise generated by a bird likely varies somewhere near the theoretical value of the *fifth power* of the flight speed, and the inverse square of the distance between the bird and its prey, doubling flight speed increases noise intensity by as much as a factor of 32. Doubling the distance between the owl and its prey

reduces the noise heard by a factor of four.

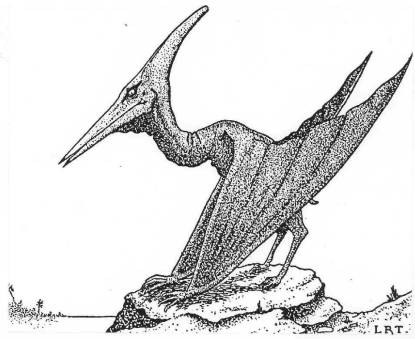
Therefore, for an owl to fly slowly (and thus with low noise) with the desired degree of maneuverability, it has a low wing loading and a large tail. The tail can act as both a flap and "rudder," and in addition there are unique micro-scale comb-like structures on the leading edges of the leading primary feathers (Fig. 5) that function as vortex generators¹⁹ that create "leading edge vortices" that serve to increase lift on the outboard portions of the wing.

To further reduce noise audible to its prey, and not interfere with its own hearing and direction finding, the owl has feathers with a remarkably velvety surface texture that reduce mechanical rubbing and rattle, and which "absorbs" higher frequency air flow noise. Further, soft feathers form a serrated trailing edge that diffuses and damps higher frequency components of airflow noise caused by merging shear layers at the trailing edge of the lifting surface.

Thus we find that owls don't really fly "noiselessly," their special adaptations merely manage the noise they generate as shown in Fig. 6 by a clever combination of suppression and frequency shifting *within the limited range of the hearing ability of their prey* until it is too late to avoid an attack.

Owls are thus very cleverly adapted for what they do (and where and when they do it), and several features of owl feathers are unique among birds (leading edge combs, velvety feathers, soft wing trailing edges). Not all owls have all these adaptations (e.g. fishing owls lack leading edge combs). Experiments¹⁹ with a live owl in which the leading edge wing combs and trailing edge fringe were clipped from the wing produced a significant deterioration in its ability to fly - and noise generated more like that of other birds. While much of this technical detail has been found to be beyond the grasp of members of a typical bird watching club, it presents a fine example of complex, integrated system design to any intelligent high school student with knowledge of simple algebra.

Pterosaurs With “Smart Wings”



While most attention outside the biological community has focused on the mysteries and inspirations of bird and insect flight, it is perhaps the extinct order Pterosauria²¹⁻²⁷ among the vertebrate fliers that potentially has the most to teach us regarding fruitful future lines of aircraft development. The fact that there are no living examples of these fantastic creatures, which because of their antiquity are thought to be “primitive” (cf. Fig. 4, and Figs. 8-11), partially accounts for their having been largely ignored as a useful model for flight vehicle design. Recent research has finally begun to demonstrate that this is but one of the many misconceptions regarding a group of flying animals whose basic design made them quite successful for a period of about 150 *million* years! The significance of this long-term (even in geologic time-scale terms) success is reinforced by the observation on evolution made by the ornithologist Karl Welty: “*Nature eradicates deviationists more cruelly and completely than any totalitarian dictator.*”

Pterosaurs were the earliest of the vertebrates to evolve the ability to fly, first appearing in the fossil record during the Upper Triassic over 200 million years ago, and finally becoming extinct with most of the dinosaurs (birds being the increasingly widely accepted exception) at the end of the Cretaceous 65 million years ago. While sharing a common reptilian ancestor with dinosaurs, and having co-existed with them for the entirety of their existence, pterosaurs were not dinosaurs and appear to have evolved far beyond the limits of the common image of “cold blooded reptiles” – despite the best efforts of Gary Trudeau and his “Far Side” cartoons to convince us otherwise. There is now fossil evidence (e.g. Sarov’s discovery of *Sordes*²⁰) that at least some species had fur for insulation suggesting that they were warm blooded with a

high metabolic rate consistent with their ability to actively fly rather than merely glide and soar. While relatively rare, fossil remains of pterosaurs have now been found showing their size range to have been from small swallow-sized creatures to monsters that hold the record for being the largest flying animals ever to have existed.

Many of the controversies and misconceptions regarding pterosaurs and how they functioned are due to the inadequacy of their fossil record and the fact that their skeletons were so fragile that key elements of their fossilized remains are often fragmented or very severely distorted. With hollow bones even more thin-walled than those of birds, one paleontologist has characterized a typical pterosaur wing fossil as closely resembling the shattered remains of a fluorescent light bulb. To make matters even more difficult, despite a growing recent list of higher quality fossil finds, the authors’ know of none that show unambiguously where the wing membrane that makes up the lifting surface attached to the posterior part of the animal. This has serious consequences in attempting to evaluate the flying behavior and characteristics of pterosaurs – especially the larger ones – and leaves open the question of whether their ancestors developed the ability to fly by first developing a membrane attached to its hind limbs like that of a bat that allowed them to glide down from a height or, as is the suspicion for birds, that they evolved from an actively running, leaping reptilian antecedent that lived primarily on the ground and developed the necessary membrane rather than feathers to provide the necessary lift (and thrust) producing surface.

In an earlier paper,²⁸ the first author presented a scenario that seems to fit most of the known facts supporting a cursorial (ground up) origin for the evolution of flight *in birds*. At the same time most paleontologists and evolutionary biologists believe that bats started as tree dwellers and gained the capability for active flight via an intermediate phase as a glider. Since “plausible” cases can be made for either origin, this arboreal versus cursorial debate within the avian community continues unabated, and is even muddier (though less acrimonious) with regard to pterosaurs. Much of this latter argument hinges on whether the pelvis and its hip socket allowed the hind legs to be oriented like those in birds (and thus permitted running and jumping) or, as recent fossils of smaller species seem to demonstrate, that the hind legs

were constrained to force a more crocodilian or lizard-like stance. Either way, the question of whether the wing membrane extended to an attachment to the thigh or ankle, thus seriously encumbering any running ability, or attached to the body in a way that left the hind legs unencumbered, has remained a major mystery. New research to be discussed presently has shed some important, though indirect, light on this topic and others that are significant to the present discussion.

What we do know is that pterosaurs existed in two sub-orders (Fig. 8): the “basal” (earlier and less developed) Rhamphorhyncoidea and the “derived” Pterodactyloidea. While there are a number of technical differences between the two types, the easy way to tell them apart is that rhamphorhynoids have tails and the pterodactyloids do not. Thus the popular name “pterodactyl” is not synonymous with the entire order of pterosaurs, and the differences in the two basic types are significant. The presence of a long reptilian tail in the rhamphorhynoids suggests that, in common with all lines of animal and insect flight evolution, these initial basal versions were (in aircraft parlance) “stability configured.” That is, the brain and control systems available had not yet fully adapted to the new demands of flight and thus the animals needed all the help they could get from being highly stable to reduce the complexity of the problems they now encountered. As their evolution continued as an overall system, the brain and control system began to catch up and the advantages of maneuverability over stability in predatory operations became obvious. Thus the creatures began to morph into “control configured” devices, shedding the tail that was no longer needed as so much extra dead weight and drag. Thus the later derived pterodactyloid configuration became the dominant model from roughly the middle of the Jurassic period (circa 170-180 million years ago) until their final extinction over 100 million years later.

As the rhamphorhynoid pterosaurs, characterized by the roughly seagull sized *Rhamphorhynchus*, demonstrated their viability, they continued to evolve in both form and, as later pterodactyloids, in size to sometimes enormous dimensions. For many years, the pinnacle of this known line of development was the magnificent, roughly 7m span, *Pteranodon ingens* (Fig. 8) from the Kansas Cretaceous. With its 2m long skull, supplanted by an elegant crest that made up half

its length, the *Pteranodon* has been the subject of much study and speculation since it was first described in 1910 by Eaton.²² One such major investigation²³ that has provided a model for the possibilities of a proper interdisciplinary approach to the study of biological problems was that conducted in Britain by Cheri Bramwell (a zoologist and chiroptologist) and George Whitfield (an engineer and sailplane pilot).

By careful examination of the near complete fossil remains, of which casts were made to allow evaluation of the probable ranges of articulation of each joint, and using plausible assumptions about the sizes and arrangements of the muscles and internal organs, based on living birds, etc., they estimated that the mass of this huge creature (with a body that was actually no larger than that of a turkey) was about 16 kg. Assuming that the wing membrane attached to the ankle (per the “traditional model” shown in Fig. 10 and by rough analogy with then current Rogallo wing hang gliders, Fig. 9) they “closed the books” to their satisfaction on the probable size-weight-flying characteristics relations of *Pteranodon* and large pterosaurs in general. They also showed that pterosaurs of *Pteranodon* size were capable of active flight by flapping their wings, but that the beasts were basically sea bird-like in their use of soaring and were better advised to launch themselves from a suitable hill or cliff as *Pteranodon*’s habitat on the shores of a vast inland sea that covered much of Kansas during the Cretaceous allowed them to do. Not all paleontologists were convinced that they had gotten it right, however, although a later, first principles-based analysis (Fig. 10), by the well-known biomechanician, R. McNeill Alexander²⁴ does lend additional credence to the work of Bramwell and Whitfield.

The subsequent discovery^{25,26} by a young graduate student, Douglas Lawson, of the truly amazing fossil remains of the gigantic “Texas Pterosaur” in what is now Big Bend National Park again cast doubt on much of the newly emerging conventional wisdom regarding large (and small) pterosaurs. Lawson named his find *Quetzalcoatlus northropi* (the species named in honor of Jack Northrop of flying wing fame), and estimated its probable wing span to be about 16m, within a possible range of roughly 13 to 20m, based on the known ratio of humerus (the upper arm bone in the analogous human skeleton, cf. Fig.4) to wing span for a range of smaller pterodactyloids. Even with a body

disproportionately small compared to its enormous and lightly built wing (of whatever configuration), conventional mass-size scaling suggested that *Q. northropi*'s mass was likely to have been in the range of at least 55-70kg for even the lowest of Lawson's span estimates.

This posed the problem that there did not appear to be enough flight muscle mass in the estimates of the total mass to have allowed the monster to get off the ground – unless it jumped off a cliff or was capable of performing some sort of running take-off aided by its legs. Lawson further noted that, at least in the Cretaceous period, there were no cliffs, mountains or other suitable geological features of the terrain in southern Texas that would have allowed it to do any sort of hang glider like take-off. [It may be noted here that this sort of notion is somewhat analogous to the common mistake made by lay aerodynamicists in seriously confusing the relation between the size of an air molecule and even a small water droplet in their encounters with any glass smooth (and possibly waxed) wing surface in terms of possible drag reduction techniques, etc. Real estate may be as 'flat as Kansas', but it is never really as flat as a billiard table in relation to the take-off field length requirements of even a huge bird or pterosaur. Much more recent experience with simple parasails as an extension of traditional hang gliding may be instructive in this regard, provided suitable winds existed during the Texas Cretaceous.]

Lawson's discovery set off quite a debate and the first author's²⁷ singular contribution to it was to point out that there was more than a passing similarity between pterosaurs wings and some basic Rogallo wing data (Fig. 9) from NASA sources. Specifically, the *high aspect ratio cylindrically cambered* model showed important performance gains relative to the low aspect ratio conically cambered version then favored in the "kite" (hang glider) community because of their inherent longitudinal stability when the keel is properly warped. Examples of large moderate aspect ratio cylindrical hang gliders had been built and successfully flown (e.g. the 1970's vintage "Cronk Kite"), but with spans of up to roughly 13m, they had proved difficult to fly and had extremely marginal *lateral* control characteristics, even with full weight shifting and using lateral keel warping control techniques combined with wing tip drag rudders. Thus it was concluded that even with the enhanced

capability of the later pterosaurs to control their wing geometry (within significant limits compared to birds and bats), it seemed highly unlikely that Lawson's span estimate of 16 m for *Q. northropi* was possible and that the lower 13 m bound was more probable (while secretly hoping that the extreme 20m span limit could be proved to be correct). As matters now stand, the 13 m span for an adult *Q. northropi* has come to be generally accepted as the probable nominal value in the pterosaur literature.

So the pterosaur debate has stood, while new and high quality fossil finds continue to be made (particularly in Brazil and China), until the very recent publication of new research on pterosaur neurophysiology by Witmer, et al,²⁹ and nicely summarized in context in a companion piece by Unwin.³⁰ With access to two relatively very well preserved skulls of a *Rhamphorhynchus* and a later pterodactyloid, *Anhanguera*, they were able to make CT scans to establish the size and shape of the brains of the two creatures. While the brain and other soft tissue is generally not fossilized, the brains in pterosaurs fit very tightly into their skulls and thus allow reasonably accurate models to be constructed. These can then be compared to the known sizes and shapes of both non-flying reptiles and extant birds, as shown in Fig. 12. What the data shows is that while the brains of pterosaurs are smaller than those of birds of equivalent size (body mass), they are substantially larger than those of equivalent non-flying reptiles.

More interesting are the significant modification of the pterosaur brains relative to each other and to those of other animals. The first notable characteristic, especially of the *Anhanguera* brain, is the hugely expanded size of the floccular lobes that serve as sensory data collectors and organizers. The second feature is a semi-circular canal surrounding the floccular lobes that in most animals is oriented horizontally. In the rhamphorhynchoid, the brain and its canal suggest that the skull was held in a roughly horizontal mode when at rest or in flight, while in the later pterodactyl, there is a very definite head down attitude when the brain and its canal are horizontal. This suggests that the stance of the two pterosaurs at rest is as shown in Fig. 12, and this in turn suggests that the more traditional model of the pterosaurs as awkward quadrupeds when on the ground is likely correct. This also happens to be consistent with what have now been identified as pterosaur track ways

in fossilized mud discovered at several sites around the world. This new data now presents yet another view of the pterosaurs which is both traditional and yet very new.

As Unwin³⁰ concludes: “*New, extraordinarily well-preserved pterosaur material...shows that the wing membranes were highly complex, containing structural fibers, blood vessels and a fine network of muscles. These features would have given the wings the ability to collect and transmit sensory information about local conditions within the membranes, enabling pterosaurs to build up a detailed map of the forces experienced by the wings from moment to moment. Processing via the floccular lobes could have allowed them to respond very rapidly, through localized contractions or relaxations of muscle fibers within the membrane and coordination with fore-and hind-limb movement. Equipped with these ‘smart wings’, pterosaurs would have had excellent flight control. Despite their antiquity, they could even have outperformed modern birds and bats.*”

While Unwin’s final remark is perhaps debatable, ignoring as it does the fact that both birds and bats have wings made of living tissue and the necessary brain apparatus to exploit this “smart sensing capability,” the new view of the pterosaur presents an intriguing glimpse of the possible future development of remarkable wing technology that can be developed with the enhanced design tools, materials, and computer and sensing instrumentation becoming available to us.

Biomechanics 101 – Scale Effects and the Square -Cube Law

The previous discussion and the two case studies presented should serve to demonstrate how a proper multidisciplinary study of biomechanics can serve the interests of both the biological science and the engineering communities. As also indicated, exposing students to these concepts is both possible and important to the aerospace community. Even high school and elementary school students can grasp some of the elements of the overall topic, and a good beginning point is the use of the simple square-cube law as shown in Fig. 13. While strictly applicable to objects of geometrically similar shape, the use of ‘spherical animals’ is

instructive in exploring both the maximum and minimum sizes such animals can be.

While the entire range of flying devices hardly meets the criteria for geometric similarity, a large collection of data can be shown (Fig.14) to follow general square-cube law trends to a rather remarkable degree over twelve orders of magnitude in mass. While there is considerable deviation from the grand trend shown, closer examination of it shows that devices as geometrically dissimilar as flying seeds, pterosaurs, and human-powered airplanes follow their own parallel square-cube law trend - largely because their fundamental design requirements (low power or low vertical velocity in a glide) seem to override their major (or are they?) geometry differences. Here one is reminded that, regardless of other concerns, the wing-sizing problem with regard to wing area is always driven by the basic relation (in which lift coefficient has definite physical bounds) such that: $0 < C_L S < C_{Lmax} S$.

The same sort of algebra-based analysis can be extended to study some interesting problems, specifically the issue of how big a soaring or gliding animal can get. Here we need not worry about the difficult and complex issues of flapping flight, but may concentrate on the puzzle shown in Figs. 15 and 16, i.e. how on earth did the enormous and now extinct *Argentavis magnificens* work and how big was it really? As shown in Fig. 17, there is a strong correlation between flight muscle mass (and thus power available) and total mass of most birds. As shown in Fig. 18, using the square-cube law without reference to any viscous scale effect benefits on drag, etc., the power required to fly increases as the mass, M , to the 7/6 power, everything else being equal. Thus taking known data for a pigeon as an anchor, one can project the curve to the point where power available exactly equals the power required at one possible flight point and show that the maximum mass of a flying bird is about 20kg as is consistent with that of a barely able to fly South African turkey, the Kori bustard.

We know, of course, that there are benefits to increasing size (cf. Fig. 3) and armed with a suitable mathematical technique (the non-linear, but conceptually simple optimization technique of *geometric programming* has long been the first author’s weapon of choice), it is relatively straight forward to show that, again everything

else being equal, if we make the assumption that the flow on the bird is entirely turbulent, then the power required would vary as M to the $65/57$ power, a relatively small difference from the square-cube law value of $7/6$, but enough to move the power available to power required cross over to a mass of 35kg , consistent with estimates for the large, extinct teratorn, *Teratornis incredibilis*. If one were to make the highly optimistic assumption that the flow on the bird is fully laminar, the power available is found to vary as M to the $9/19$ power and we get something like the middle range of span for our *A. magnificens*. Further calculations along these lines are left to the interested student.

This sort of analysis still leaves open the question of the size-power requirements for the pterosaurs discussed earlier, and the whole question of why dinosaurs, etc. of huge size existed on the earth at one time, but do not now. The usual theory is that the earth atmosphere was “different” then than now, perhaps being more oxygen rich. One theory never seen in any published sources is proposed in Fig.19. While improbable, it does have the virtue of offering a very simple lesson in Newton’s universal law of gravitation, that still govern much of our day-to-day experience. Again nothing more than simple algebra, a little thought, and perhaps a useful way to think about what 100 million years feels like. On a more practical level, the fine recent book by Steve Vogel³¹ is highly recommended for those interested in biomechanics.

The Perennial Engineering Question



Various attempts to present the preceding case studies and related material to our students (and professional colleagues) as good examples of integrated system design generally draw the response: Well, all that is somewhat interesting, we suppose, but....what do you *do* with it? Try to design better butterflies?” Ah, well let us show you a few example possibilities. Before considering some specific examples, however, it

is worth offering the general recipe shown in Fig. 20. The message in it is that if one is avoid the trap of producing Rube Goldberg-like flying machines in trying to closely emulate nature’s models of birds or insects, it is necessary to carefully examine the system and understand the underlying physics, before dashing off and merely copying what is before us.

That point made, Figs. 21-23 are offered as examples of possible ways to deal with the morphing airplane problem and particularly with respect to UCAV applications. Much more interesting, is the material shown in Fig. 24 on non-planar wings, the origin of which was the puzzle presented by the splayed pinion feather of large soaring bird wings. Most of the schemes shown do not look anything like the pinion feather, but the entire explanation is based on the same basic physics, and some of the schemes shown are actually practical for airplane applications as shown in Fig. 25.

Some Conclusions of a Continuing Work in Progress

We have made amazing progress during the first century of powered human flight in terms of farther, faster and higher - and we have far excelled all of nature’s fliers in these regards. On the other hand, we have yet to develop a self-repairing airplane that can lay eggs and reproduce itself. In the case of the DARPA project noted earlier, perhaps there is more potential in the development of “cloning” rather than “morphing” structural technology. Regardless of the potential applicability of natural models to the solution of human-scale technical problems, the study of the paleoecology (the *whole* system) of natural flight makes a grand hobby, encompassing life, the universe and just about everything else. At a minimum it also provides some of the inspirational tent poles that keep our imaginations from collapsing around us. Selective reading of the bibliographical material listed in this paper in the sense shown in Fig. 26 should give an adequate flavor of a very rich and rewarding field of such further inquiry.

When the author first discovered the possibilities these sources offered, it was considered largely frivolous by both his peers and mentors in the traditional engineering community. Fortunately, thanks to the major contributions made since

then by engineering scientists and mathematicians like Sir James Lighthill and the legion of subsequent investigators they have inspired, this is no longer the case and much of real value has since been learned. It also reminds us that it is useful at intervals to stand far back from what one is doing on a day-to-day basis and look at one's work in a "geological time" perspective. The effort can be refreshing and enormously humbling.

"O you who love clear edges more than anything...watch the edges that blur."

Adrienne Rich
American poet

Acknowledgements and a Disclaimer

The authors owe a substantial debt to many individuals who have contributed thoughts or inspirations used in this paper. While too many to list exhaustively, several must be acknowledged for their singular importance. These include: Robert E. Spitzer, The Boeing Company; Michael S. Francis, DARPA; Geoff Spedding, USC; Ilan Kroo, Stanford; Steve Vogel, Duke; Terry Weishaar, Purdue; Jim Schneider, Dayton, OH; and Paul MacCready, AeroVironment Inc. This paper remains an ongoing work in progress and reflects the authors' own opinions that may not necessarily reflect the views or positions of their respective employers. We made this all up, and remain solely responsible for its contents.

References

1. McMasters, J.H. and Cummings, R.M., "Airplane Design – Past, Present and Future," *Journal of Aircraft*, Vol. 39, No. 1, Jan.-Feb. 2002, pp. 10-17. [also AIAA Paper 2001-0535, Jan. 2001.]
2. McMasters, J.H. and Cummings, R.M., "The Demise of Aerospace – We Doubt It," *Flight Journal*, Aug. 2001, pp. 97-8.
3. McMasters, J.H. and Cummings, R.M., "Airplane Design as a Social Activity: Emerging Trends in the Aerospace Industry," AIAA Paper 2202-0516, Jan. 2002.
4. McMasters, J.H. and Cummings, R.M., "From *Farther, Faster, Higher to Leaner, Meaner, Greener* – Future Directions in Airplane Design in the New Century," AIAA Paper 2003-0553, Jan. 2003 [in press for publication in the *Journal of Aircraft*, 2004].
5. McMasters, J.H. and Cummings, R.M., "Rethinking the Airplane Design Process – an Early 21st Century Perspective," AIAA Paper 2004-0693, Jan. 2004.
6. McMasters, J.H., "Some Systemic Issues in the Development of the Aerospace Industry Technical Workforce of the Future," AIAA Paper 2004-1376, Jan. 2004.
7. McMasters, J.H., "Reflections of a Paleoaerodynamicist", *Perspective in Biology and Medicine*, Vol. 29, No. 3, Part 1, Spring 1986, pp. 331-84 [based on AIAA Paper 84-2167, Aug. 1984].
8. McMasters, J.H., "The Flight of the Bumblebee and Related Myths of Entomological Engineering," *American Scientist*, Vol. 77, Mar.-Aug. 1989, pp. 164-9.
9. McMasters, J.H. and Chen, M.K., "From Paleoaeronautics to *Altostratus*- A Technical History of Soaring," *Soaring*, Pt. 1, May, 1983, pp.30-7; Pt. 2, June, 1883, pp. 30-5.
10. Lillienthal, O., *Bird Flight as the Basis of Aviation*, Reprinted by Narkowski International Publishers, Hummertown, PA, 2001.
11. Anderson, J.D. Jr., *The History of Aerodynamics: And Its Impact on Flying Machines*, Cambridge: Cambridge University Press, 1997.
12. Dickinson, M.H., "Come Fly with Me," (Cal Tech) *Engineering and Science*, Vol. LXVI, No. 3, 2003, pp.10-19 [see <http://www.dickinson.caltech.edu>].
13. Daniel, T., "Implantable Microelectronics and Flight Control in *manduca sexta* (hawk moths)," <http://faculty.washington.edu/danielt/research.html>.
14. DeLaurier, J., "The Development and Testing of a Full-Scale Piloted Ornithopter," *Canadian Aeronautical and Space Jour.*, Vol. 45, No.2, June 1999, pp.72-82.
15. Azuma, A., *The Biokinetics of Flying and Swimming*, Tokyo: Springer-Verlag, 1992.

16. Dudley, R.T., *The Biomechanics of Insect Flight*, Princeton: Princeton University Press, 2000.
17. Spedding, G., Rosén, M., and Hederström, A., "A Family of Vortex Wakes Generated by a Thrush Nightingale in Free Flight in a Wind tunnel Over Its Entire Natural Range of Flight Speeds," *Jour. of Exp. Biology*, Vol 206, 2003, pp. 2313-44.
18. Lilley, G.M. "A Study of the Silent Flight of the Owl," AIAA Paper 98-2340, June 1998.
19. Schneider, J. Personal communication regarding unpublished work done in the early 1970s at the AF Institute of Technology.
20. Wellnhofer, P., *Prehistoric Flying Reptiles (Pterosaurs)*, NY: Barnes and Noble, 1996.
21. The Pterosaur Data Base, www.pterosaur.co.uk/.
22. Eaton, G.F., "Osteology of *Pteranodon*," *Mem. Conn. Acad. Art. and Sci.*, Vol. 2, pp.1-38.
23. Bramwell, C.D., and Whitfield, G.R., "Biomechanics of *Pteranodon*," *Philos. Trans. R. Soc. London, B*, Vol. 267, 1974, pp. 503-81.
24. Alexander, R. M., *Dynamics of Dinosaurs*, NY: Columbia Univ. Press, 1989.
25. Lawson, D.A., Pterosaur for the latest Cretaceous of West Texas: Discovery of the Largest Flying Creature," *Science*, Vol. 187, 1975, pp. 947-8.
26. Langston, L.W., "Pterosaurs", *Sci. Am.*, Vol. 244, No 2, 1981, pp.93-102.
27. McMasters, J.H., "Aerodynamics of the Long Wing Pterosaur", *Science*, Vol. 191, 1976, p.899.
28. McMasters, J.H., "The Origins of Flight - A Brief History of Unconventional Applied Aerodynamics", AIAA Paper 99-0115, Jan. 1999.
29. Witmer, L.M., Chatterjee, S., Franzosa, J. and Rowe, T., "Neuroanatomy of Flying Reptiles and Implications for Flight, Posture and Behavior," *Nature*, Vol. 425, 30 Oct. 2003, pp. 950-3.
30. Unwin, D.M., "Smart-Winged Pterosaurs," *Nature*, Vol. 425, 30 Oct. 2003, pp. 910-11.
31. Vogel, S., *Comparative Biomechanics*, Princeton: Princeton University Press, 2003.
32. Lighthill, J., *Mathematical Biofluidynamics*, Philadelphia: Society for Industrial and Applied Mathematics, 1975.
33. Lighthill, J., "Some Challenging New Applications for Basic Mathematical Methods in the Mechanics of Fluids That Were Originally Pursued With Aeronautical Aims," *Aeronautical Journal*, February, 1990, pp. 41-52.

Bibliography

- Alexander, D. E., *Nature's Fliers- Birds, Insects and the Biomechanics of Flight*, Baltimore: Johns Hopkins University Press, 2000.
- Alexander, R.M., *Exploring Biomechanics*, NY: Scientific American Library, 1992.
- Feduccia, A., *The Origin and Evolution of Birds*, New Haven: Yale University, Press, 1996.
- Hertel, H., *Structure-Form-Movement*, NY: Reinhold, 1966.
- Lighthill, J., *Mathematical Biofluidynamics*, Philadelphia: Society for Industrial and Applied Mathematics, 1975.
- _____, "Some Challenging New Applications for Basic Mathematical Methods in the Mechanics of Fluids That Were Originally Pursued With Aeronautical Aims," *Aeronautical Journal*, February, 1990, pp. 41-52.
- McMahon, T.A. and Bonner, J.T., *On Size and Life*, NY: Scientific American Library, 1983.
- McMasters, J.H., "Some Opportunities for Progress in Ultra-Light Aeronautics," *Soaring*, June 1975.
- _____, "Aerodynamics of the Long Pterosaur Wing," *Science*, Vol. 191, 1976, p. 899.
- _____, "Advanced Concepts for Variable Geometry Sailplanes," *Soaring*, 1980, Pt. I, April, Pt. II, May; Pt. III, June; Pt. 4, Dec.
- _____, Cole, C.J., and Skinner, D.A., "Man-Powered Flight," *AIAA Student Journal*, Apr. 1971.
- _____, and McLean, J.D., "The Formation Flight of Human-Powered Aircraft Across the English Channel in the Spring," XVIth Congress of the *Organization et Scientifique Technique Internationale du Vol-a-Voile [OSTIV]*, Château roux, France, 1980. [Published

- in *Swiss Aero Revue*, Dec. 1979 and Jan. 1980.]
- Nachtigall, W., *Warum die Vogel Fliegen*, Hamburg: Rasch und Rohring, 1985.
- Norberg, U.M., "Morphological Adaptations for Flight in Bats," in *Bat Biology and Conservation*, Kunz, T.H. and Racey, P.A. (eds), Washington: Smithsonian Institution Press, 1998.
- Ostrom, J.H., "Archaeopteryx and the Origin of Flight," *Quart. Rev. Biol.* Vol. 49, 1974, pp.27-47.
- Padian, K. and Chiappe, L.M., "The Origin of Birds and Their Flight," *Scientific American*, Vol. 278, No. 2, Feb. 1998, pp. 38-47.
- Pedley, T.J. (ed.), *Scale Effects in Animal Locomotion*, London: Academic Press, 1977.
- Pennycuik, C.J., *Newton Rules Biology*, Oxford: Oxford University Press, 1992.
- Shipman, P., *Archaeopteryx and the Evolution of Bird Flight*, NY: Simon & Schuster, 1998.
- Tennekes, H., *The Simple Science of Flight-From Insects to Jumbo Jets*, Cambridge: MIT Press, 1996.
- Vogel, S., *Comparative Biomechanics*, Princeton: Princeton University Press, 2003.
- _____, *Life in a Moving Fluid*, Princeton: Princeton University Press, 1982.
- _____, *Life's Devices* (2nd ed.), Princeton: Princeton University Press, 1997.

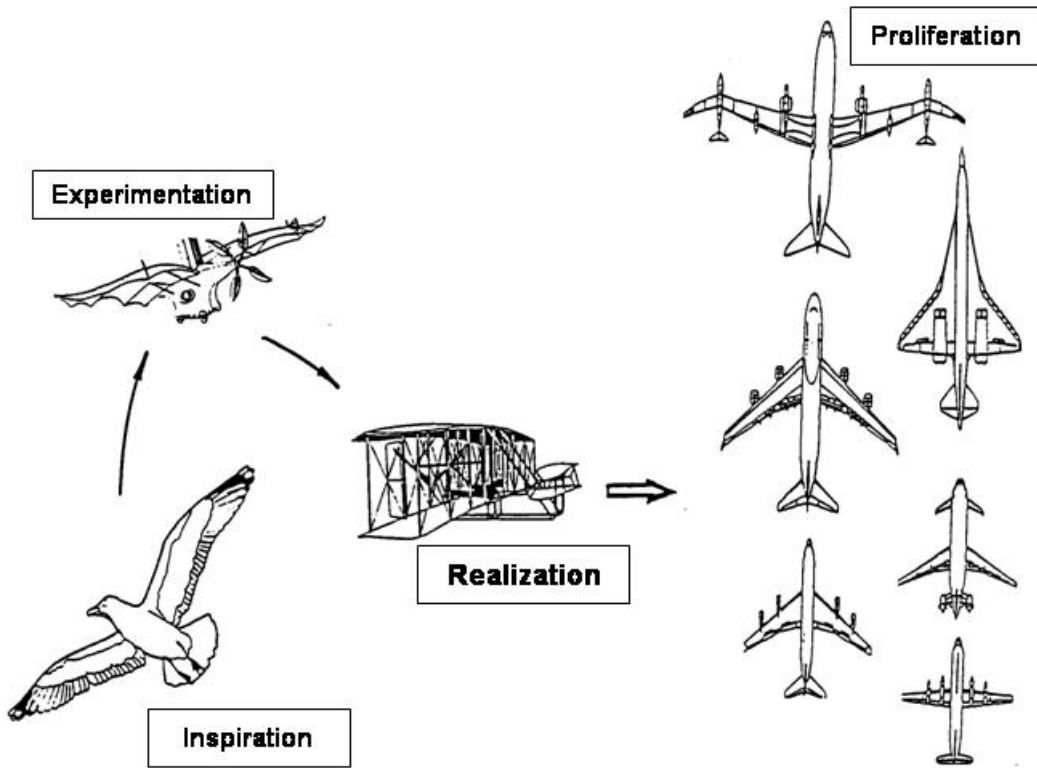


Figure 1. The Traditional Version of Aviation History.

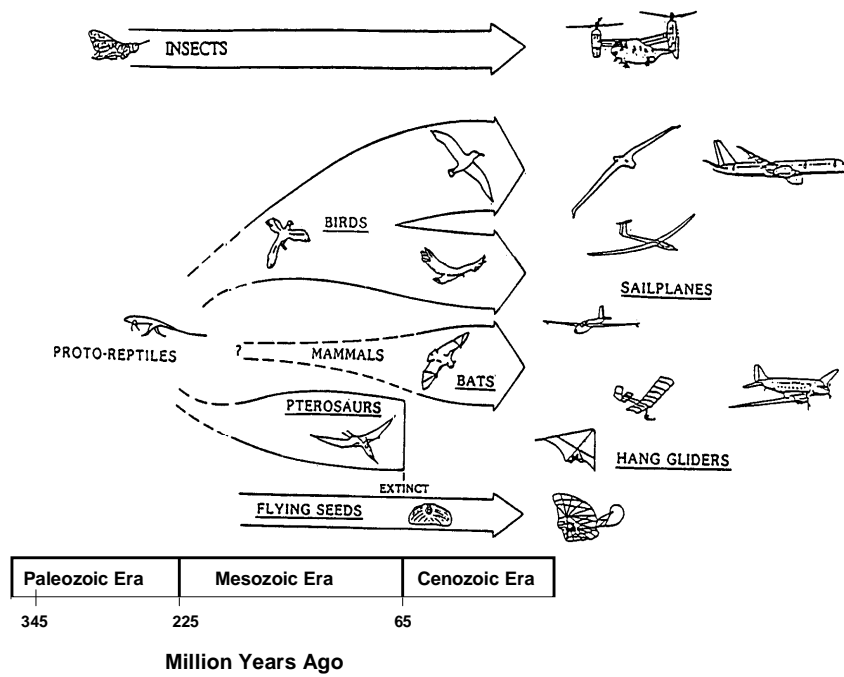


Figure 2. A More Complete Version of the History of Aviation.

Transport Economy Index = Energy Consumed per Unit Weight per Unit Distance Traveled

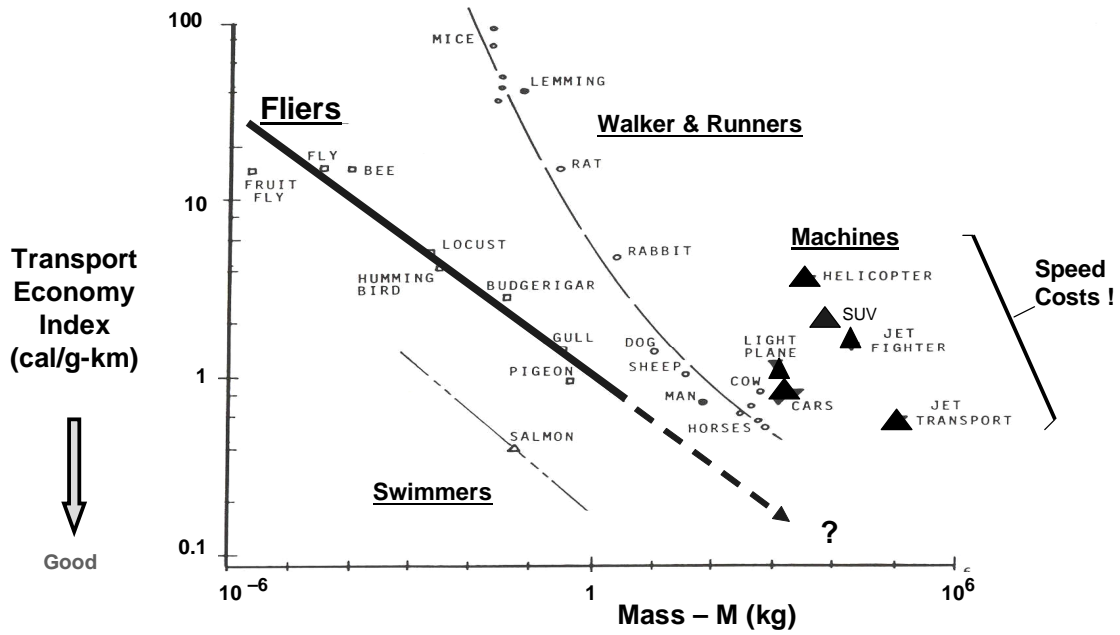


Figure 3. The Effect of Size on the Economy of Various Forms of Locomotion.

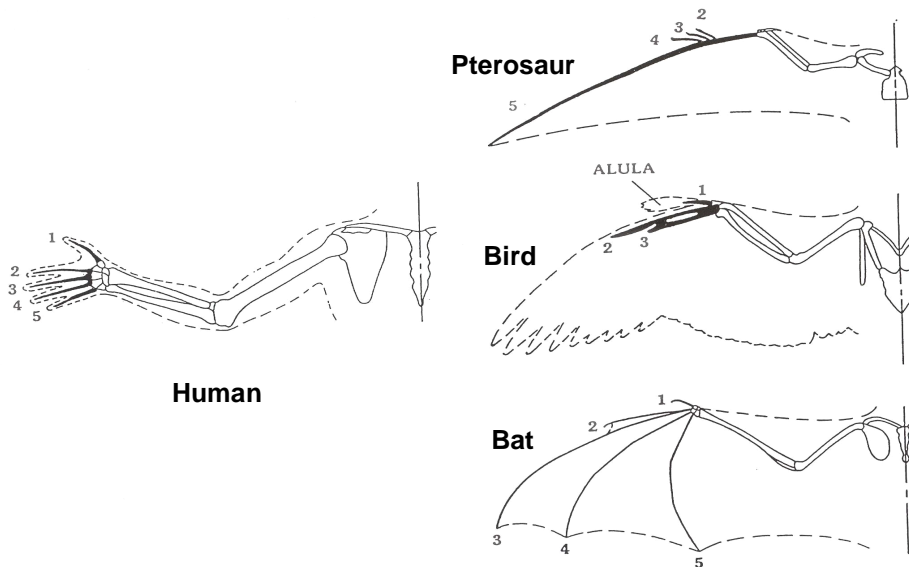


Figure 4. Different Ways to Create a Wing From the Same Basic Set of Bones.

Important Aeronautical Technology Incorporated In Birds

- Mission Adaptive Wing
- Active Controls/ Control Configured Vehicles
- Composite structures
- Damage Tolerant Structures
- Fully integrated System Design
- Advanced Manufacturing Techniques

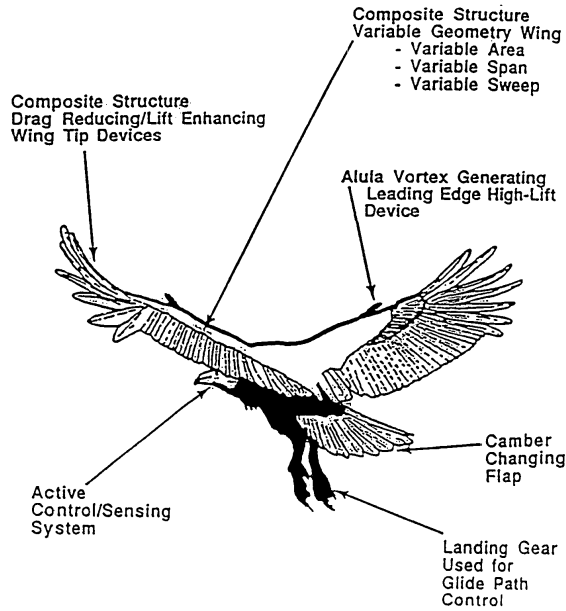


Figure 5. Modern Aeronautical Technology Embodied in a Bird.

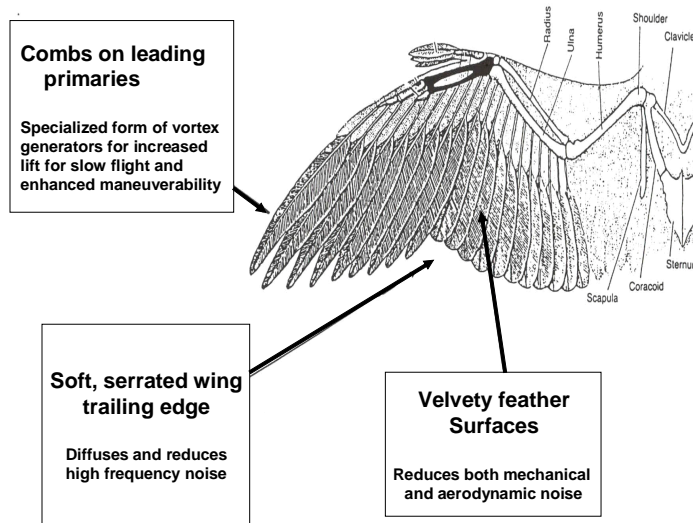


Figure 6. The Unique Feather Adaptations of Owls.

The “Silent” Flight of Owls:

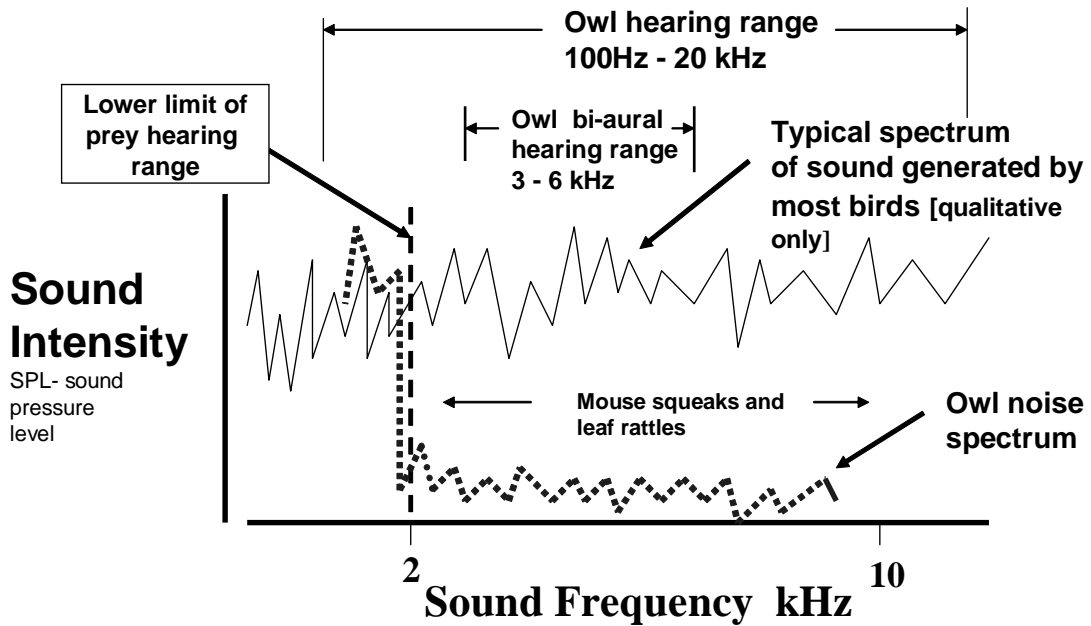


Figure 7. The Noise Spectrum of an Owl in Comparison with their Prey and Other Birds (notional spectrum).

A Natural Model of Cylindrically Cambered Rogallo Wings

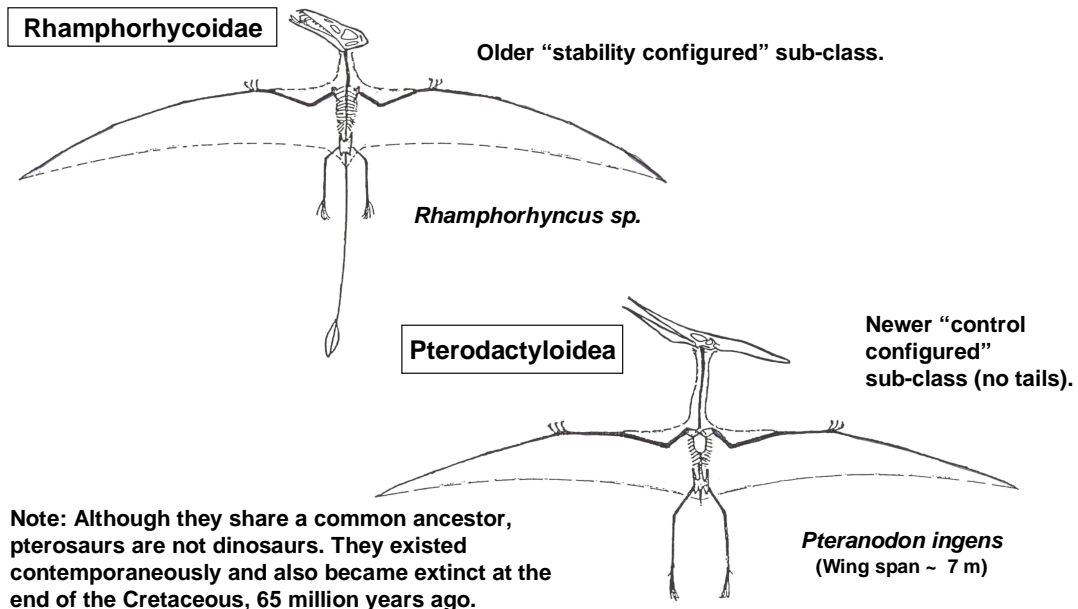


Figure 8. The Two Types of Pterosaurs.

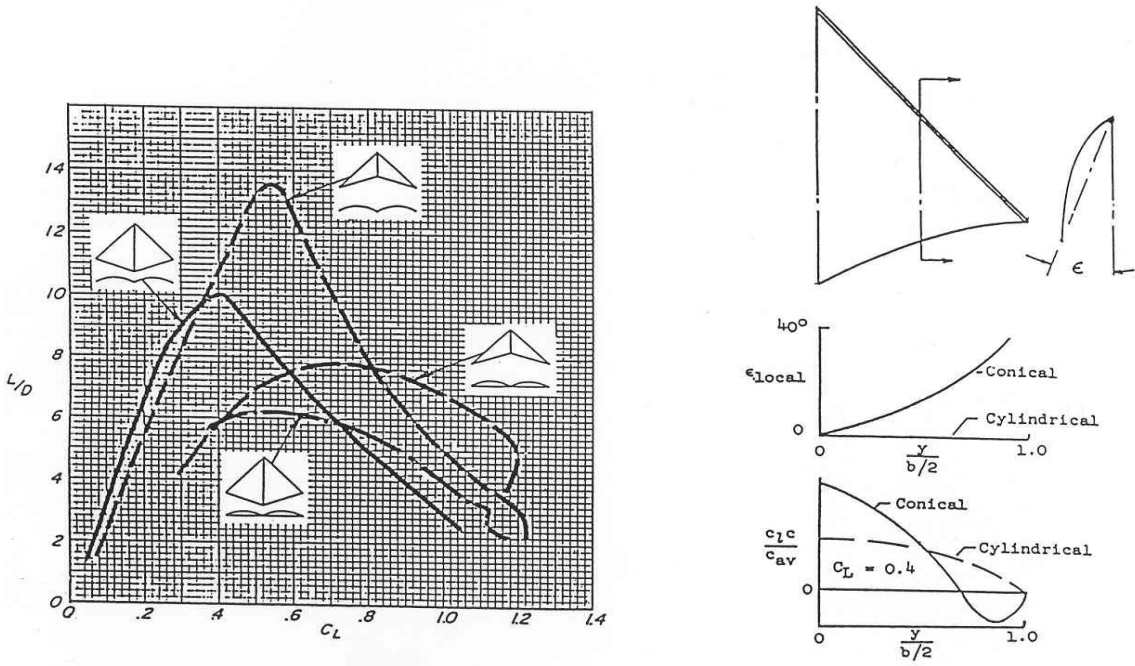


Figure 9. Characteristics of the Two Classic Forms of Rogallo Wings.

The two model shown are based on different assumptions regarding the form of the pelvis, and thus the manner in which the legs can be articulated relative to the body.

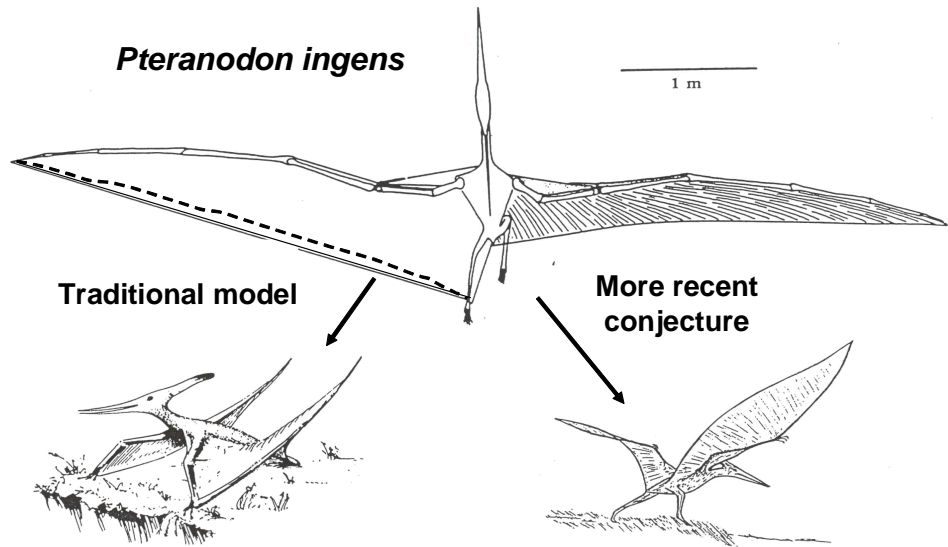


Figure 10. Two Possible Models for the Wing Membrane of *Pteranodon*.

The Texas Pterosaur (*Quetzalcoatlus northropi*)
from the Cretaceous Era ~ 70 million years ago

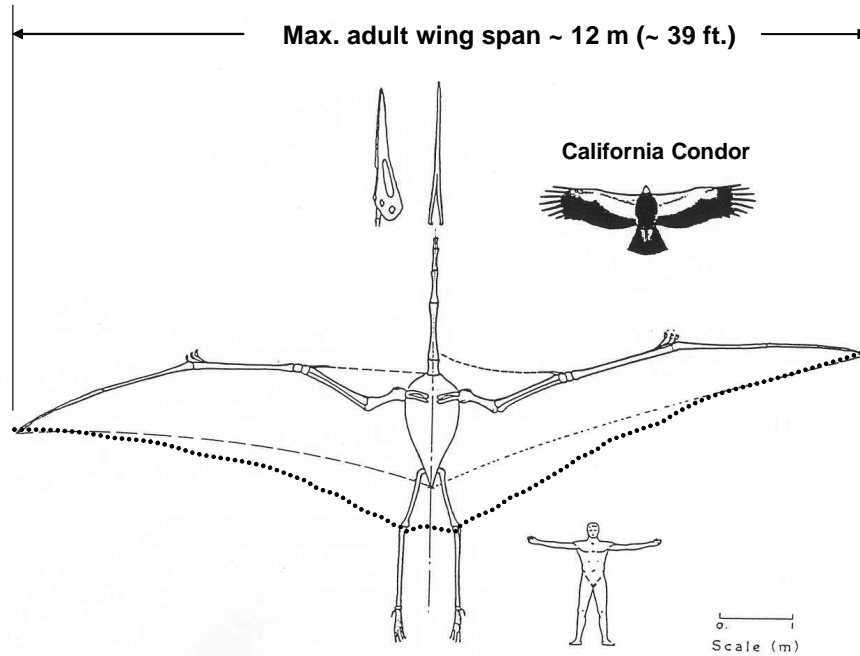


Figure 11. The Largest Known Flying Animal – A Pterodactyloid Pterosaur.

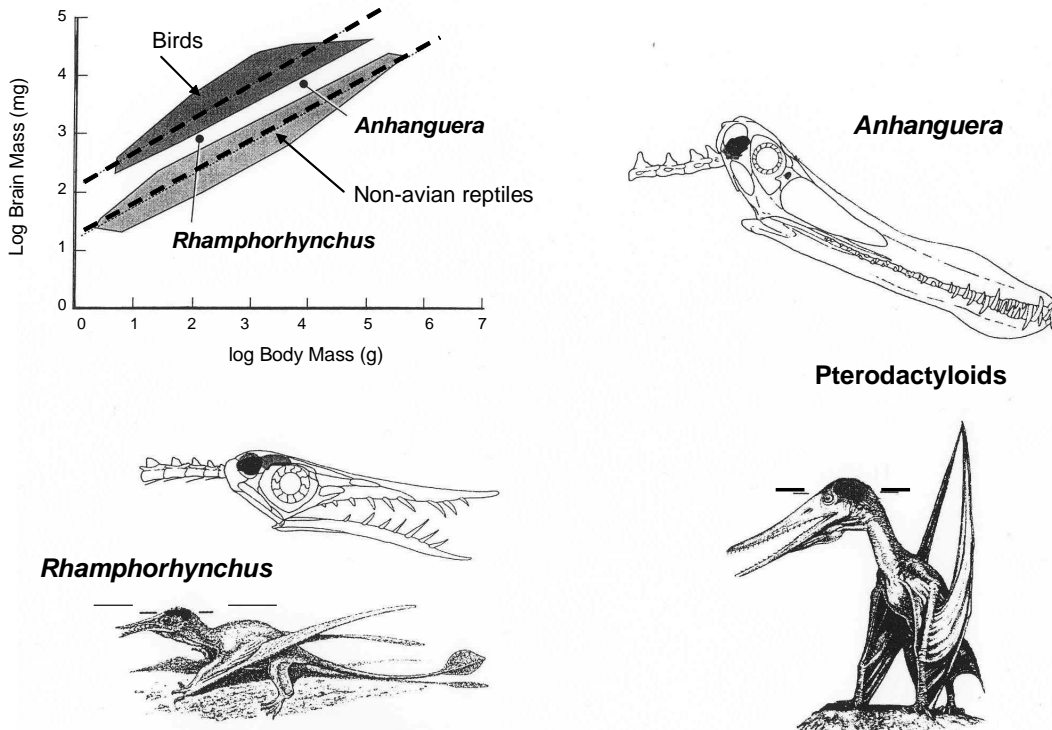


Fig. 12. Pterosaur Brains in Comparison to Those of Birds and Non-Flying Reptiles.

For "Geometrically Similar" Animals.....

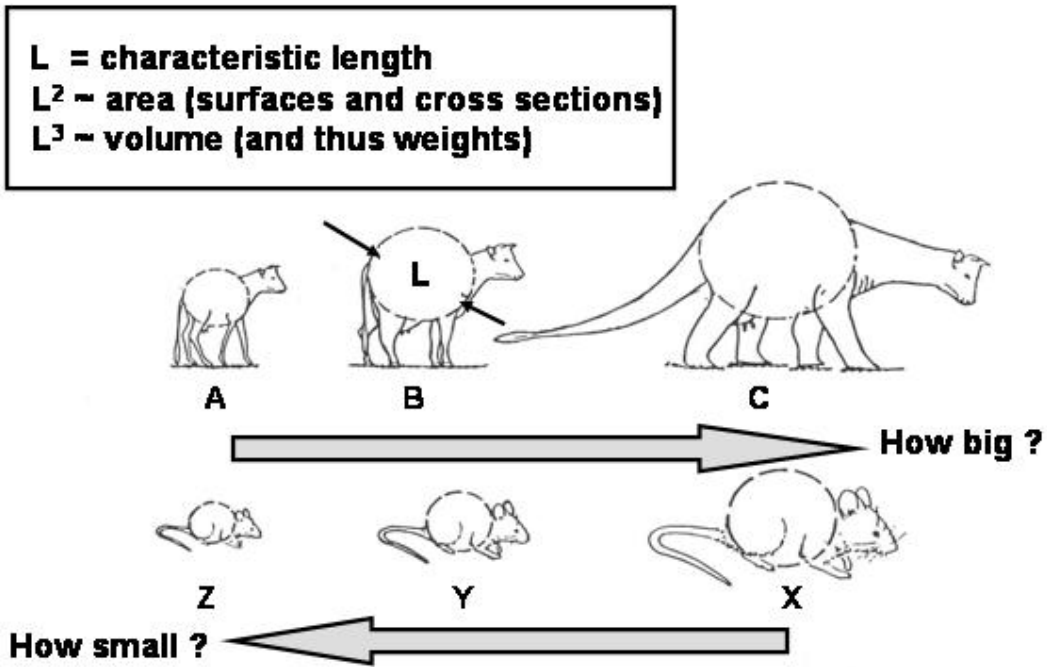


Figure 13. The Square-Cube Law.

Despite a lack of strict geometric similarity..

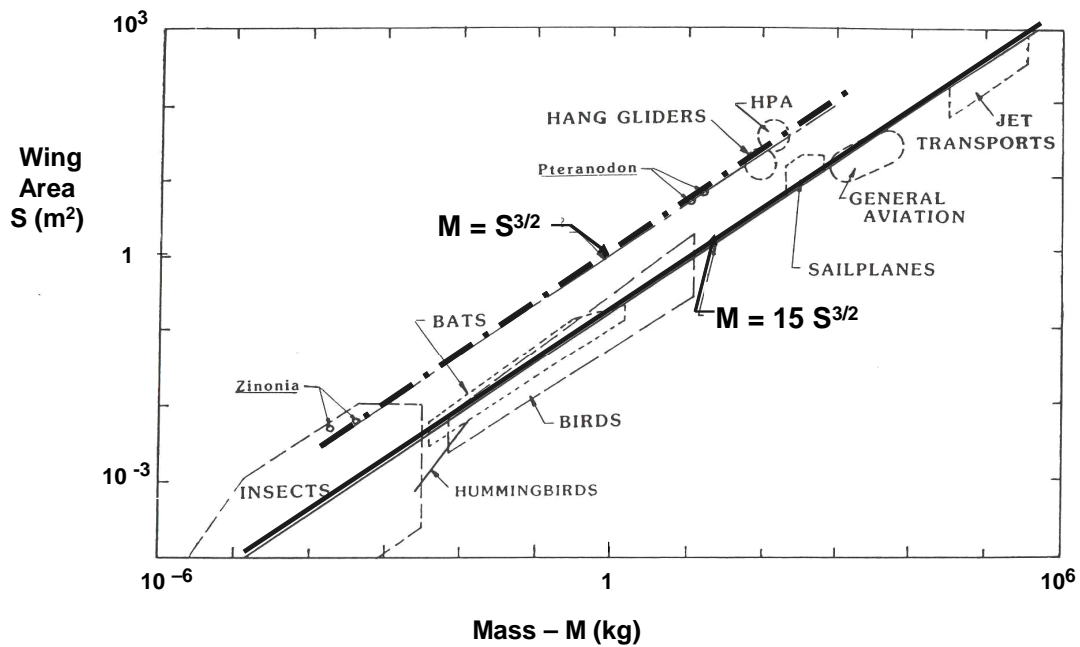


Figure 14. Mass-Wing Area Relations Among Fliers.

Different Soaring Modes and Environments ↔ Different Geometries

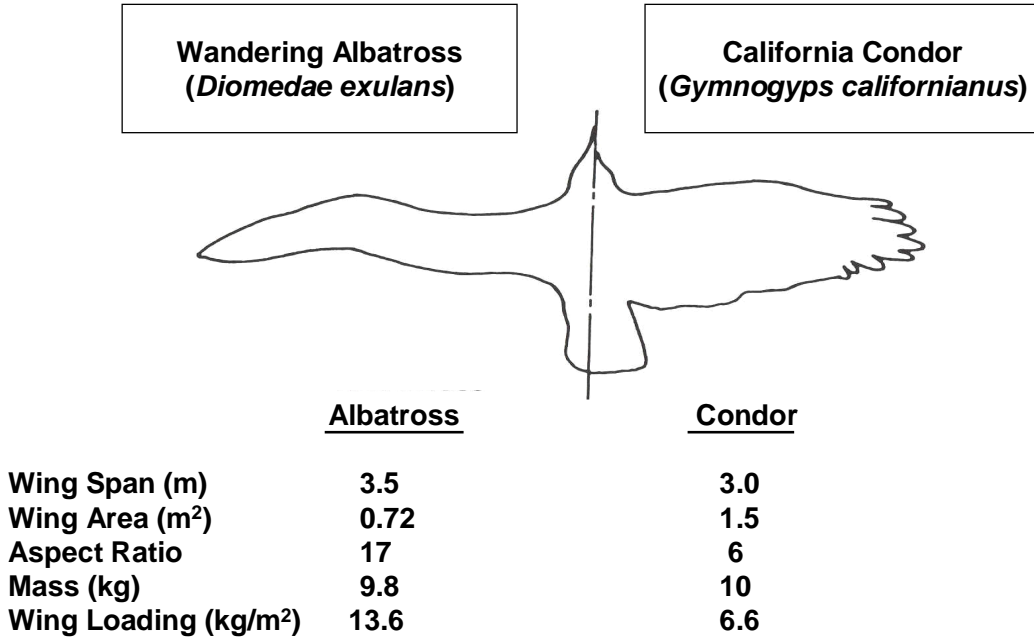


Figure 15. Examples of the Largest Extant Soaring Birds.

Argentine Teratorn (*Argentavis magnificens*)
 Argentine Miocene 7 million years ago

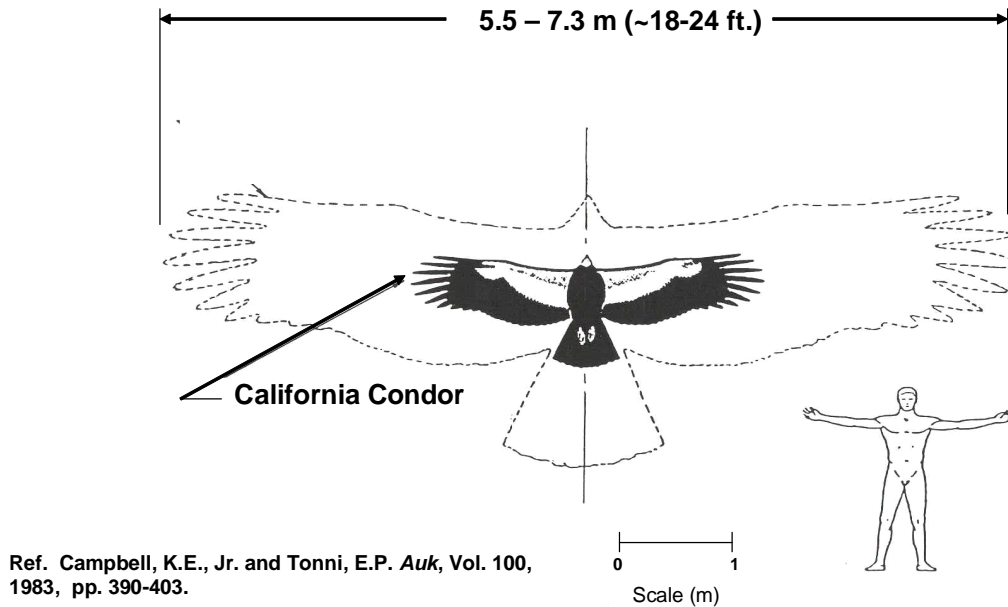


Figure 16. The Largest Known Bird – *Argentavis magnificens*.

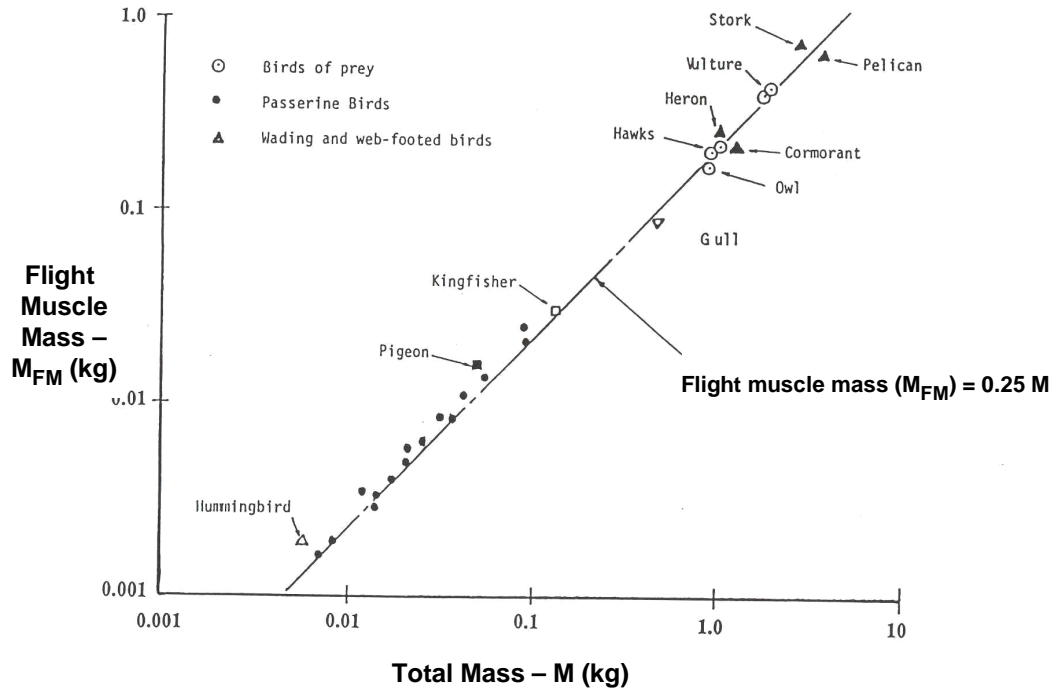


Figure 17. Relationship Between Flight Muscle (and Hence Power Available) and Total Mass in Birds.

According to the Square-Cube Law....

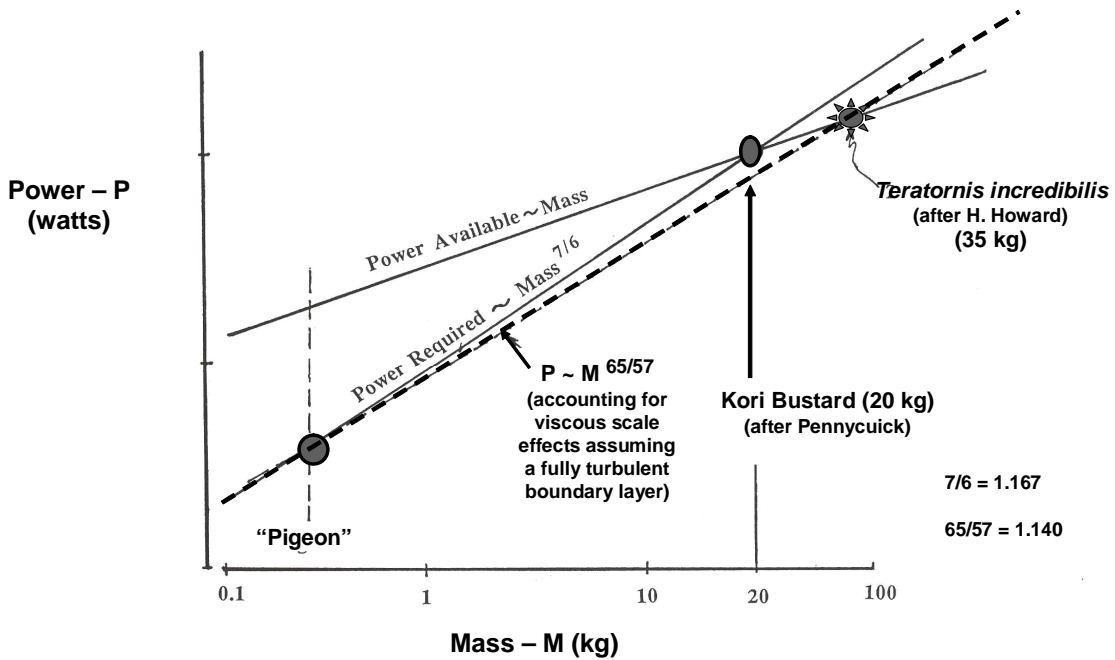
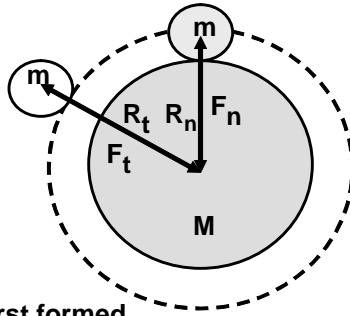


Figure 18. Accounting for Reynolds Number Scale Effects in the Context of the Classic Square-Cube Law.

The Shrinking Earth Hypothesis

For which there is currently no shred of evidence - yet.

This example represents an average, almost undetectable change in diameter of less than three meters per century !



$$F = k M m / R^2$$

Where:

F = mutual force of attraction (or weight of object of mass m)

M = mass of the earth

R = distance between the centers of the two masses

K = universal gravitational constant

Assume the Earth has been shrinking as it cools since it first formed.....

Thus: If, say 100 my bp, R_t was 20% larger than now ($R_t = 1.2 R_n$), and M and m are constant over time, the same object (m) on or near the surface of the Earth would have weighed 31% less then than it does now ($F_t = 0.69 F_n$).

Figure 19. Gravity According to Newton – One Possible Explanation for the Past Existence of Really Large Animals.

Bionics Process Flow for Devices of Similar Operational Type

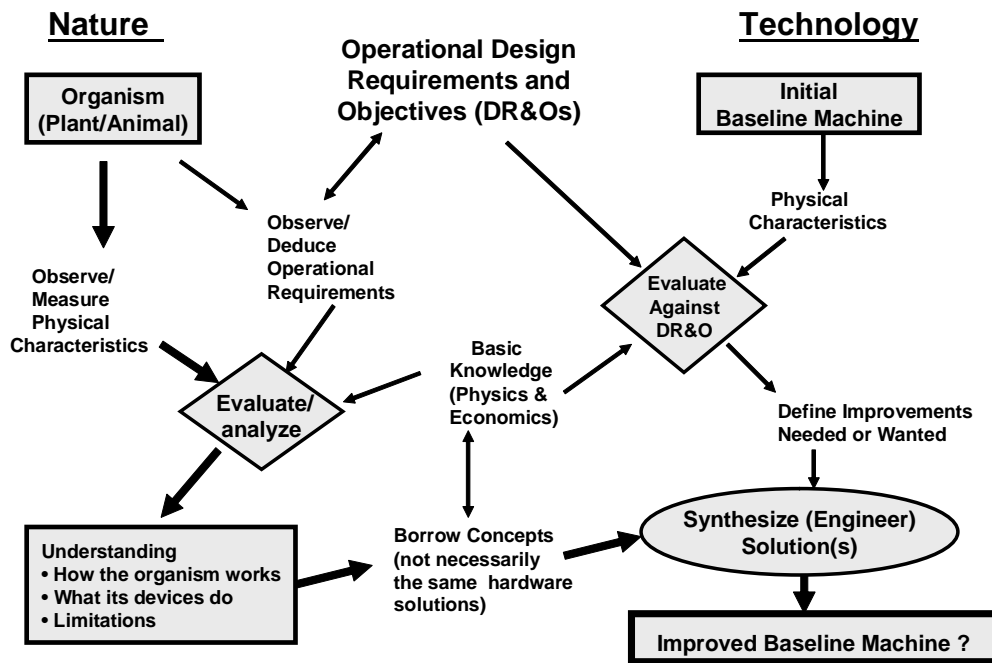


Figure 20. Process Flow Diagram for Use of Biomechanical Concepts in Aeronautical Applications.

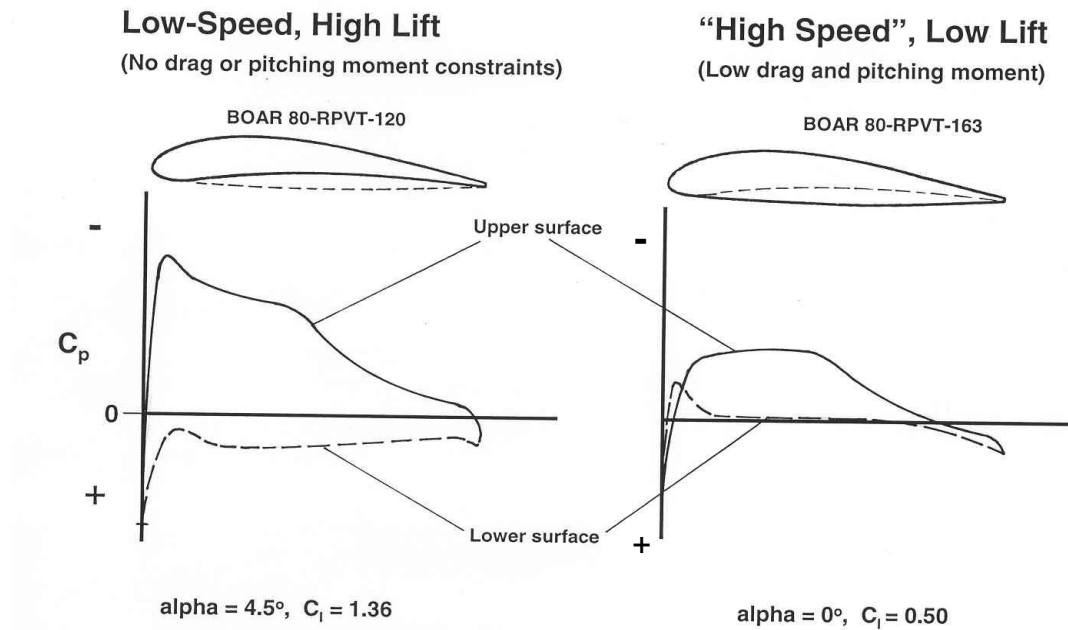


Figure 21. A Variable Thickness and Camber Airfoil Concept for a Small Sailplane.

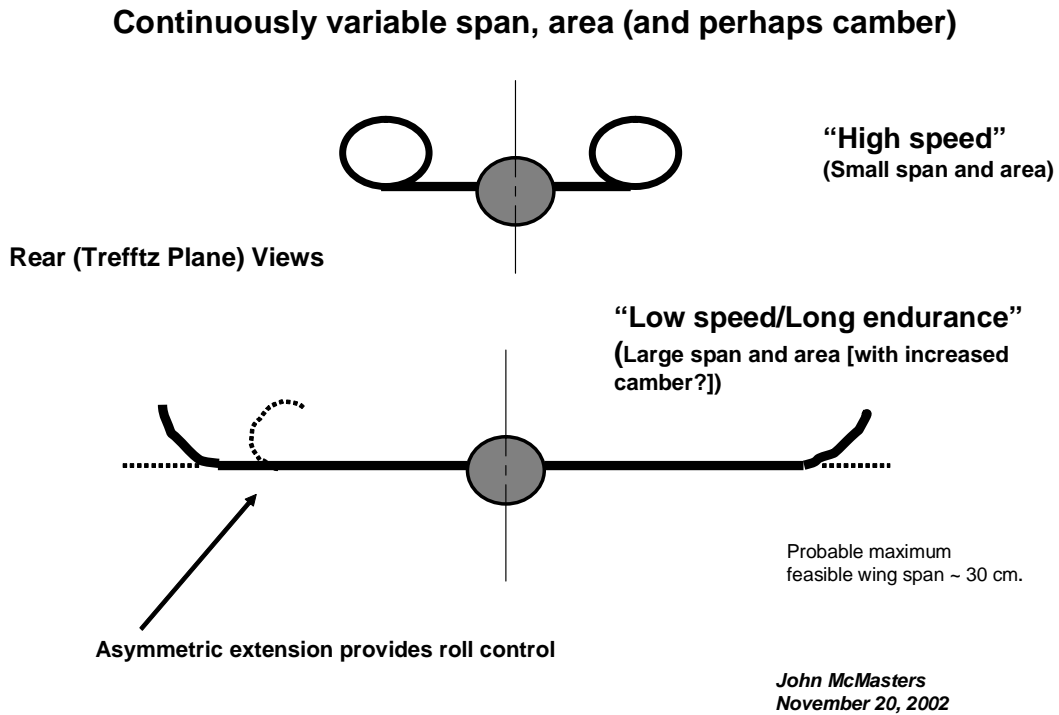


Figure 22. John’s Coil-Wing (Party-Favor) UCAV Configuration Concept.

The Formation Flight of UCAVs Across the World in the Spring or Whenever

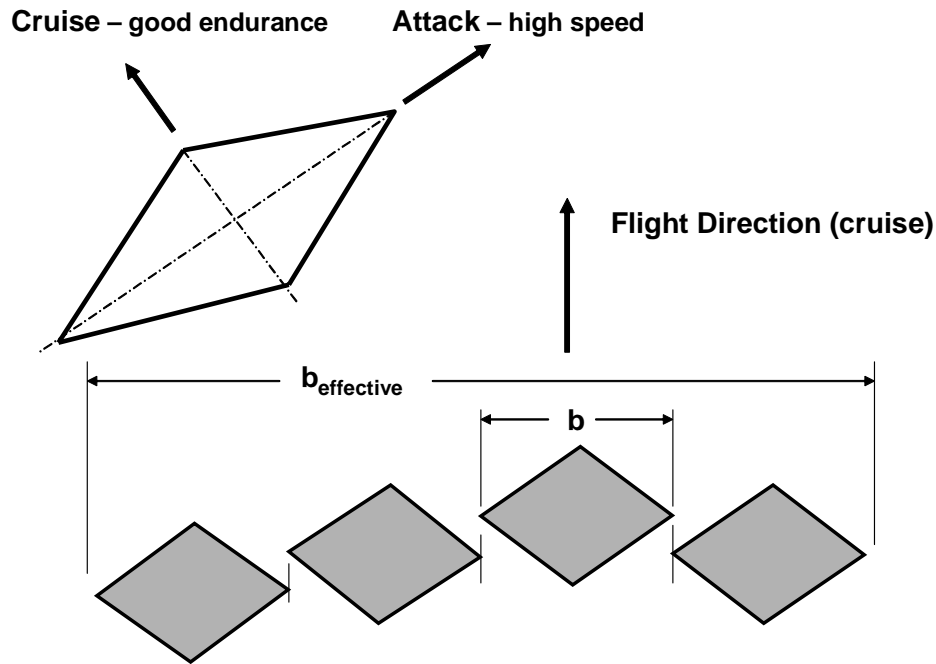


Figure 23. A Possible “Simplified” UCAV Configuration (thanks to Ilan Kroo).

Constant wing span (b), area (S) and height-to-span ratio [h/b=0.2]

Induced Drag (drag due to lift) = $D_i \sim k [Lift (L)/span (b)]^2 \times speed (V)^{-2}$

k = theoretical wing span efficiency factor

In steady, level flight,
Lift (L) = Weight (W)

Note: For an optimally loaded planar wing of the same span and area, k = 1.0

		Biplane	k = 0.74		Joined wing	k = 0.95
		X-wing	k = 0.75		C-Wing	k = 0.69
		Branched tips ("pfeathers")	k = 0.76		Tip plated winglets	k = 0.83
		Tip plates	k = 0.72		Winglets	k = 0.71
		Box biplane	k = 0.68		Dihedral	k = 0.97

Treffetz plane analyses due to Prof. Ilan Kroo, Stanford University (circa 1992).

Aspect ratio = b^2/S

Figure 24. Non-Planar Wings (By Analogy with the Pinion Feathers of Birds).

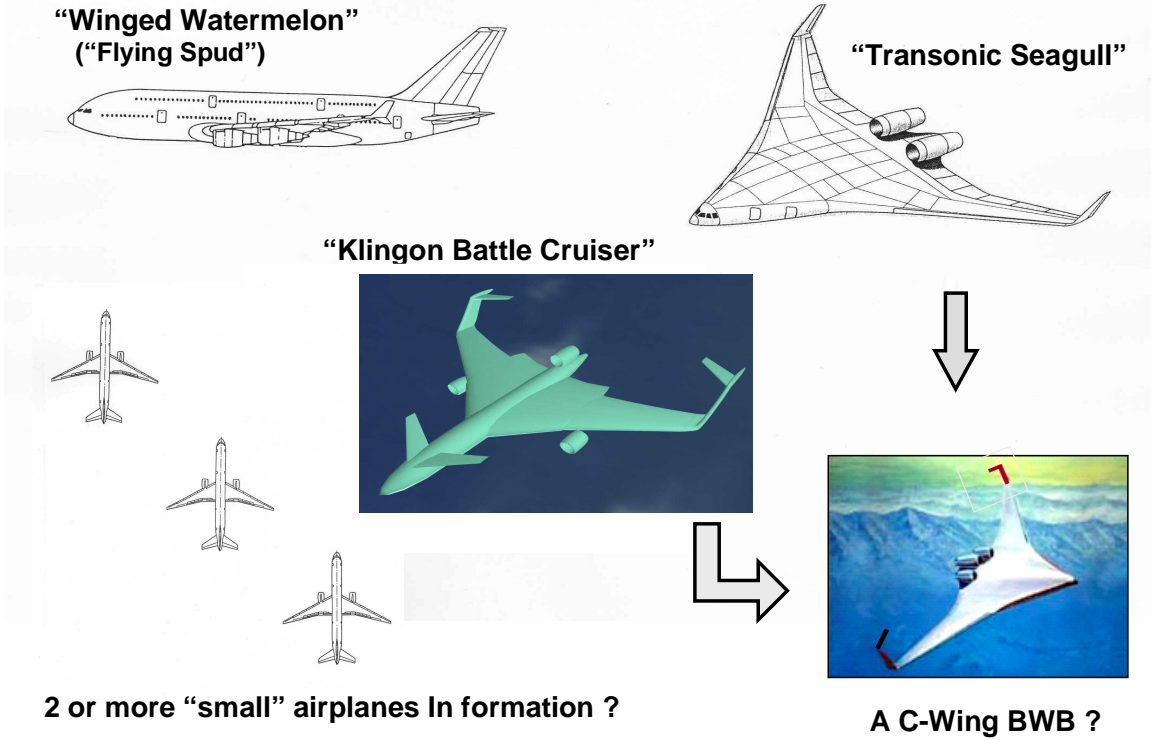
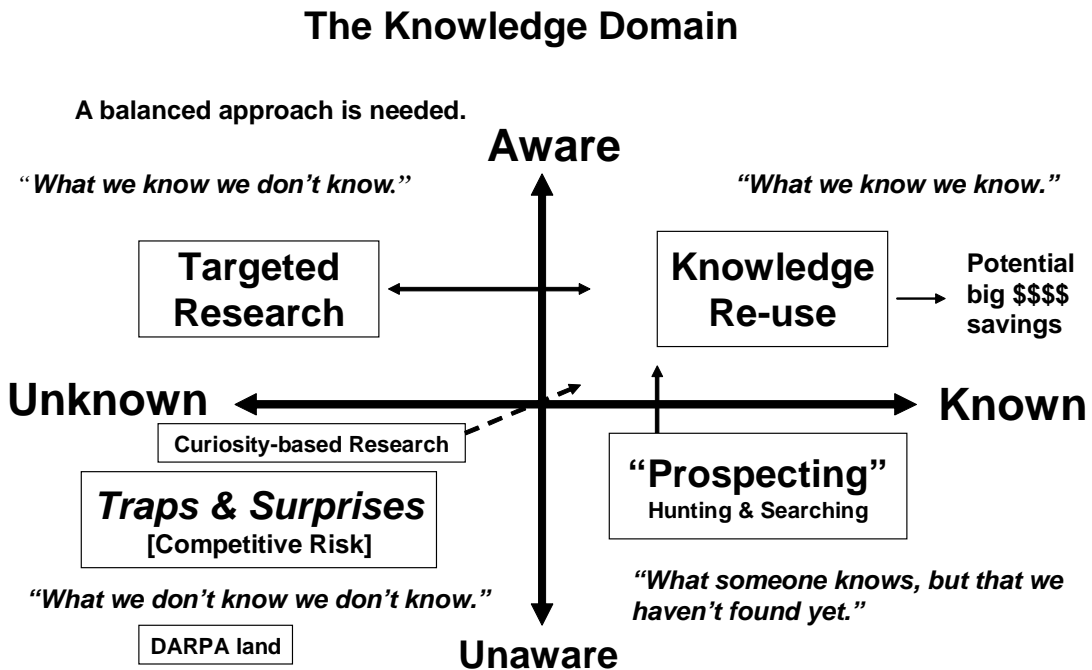


Figure 25. Some Biomechanics Inspired Options for *Very Large Airplanes*.



Originally developed by Dr. Lee Matsch [Allied Signal Aerospace] and John McMasters under the auspices of the Boeing initiated Industry-University-Government Roundtable for Enhancing Engineering Education [UGREEE] in 1997-98.

Figure 26. Exploring the Knowledge Domain.