Paleoaerodynamic Explorations - Part 1: Evolution of Biological and Technical Flight

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"Paleoaerodynamics can be defined as a rich field, imbued with a long and interesting past and an even more intriguing and hopeful future". This presentation, part 1 of a two part presentation, will focus on the long and interesting past. Part 2 will focus on the intriguing and hopeful future. This presentation will provide a glimpse of insights and observations of some fascinating aspects of birds, insects and flying seeds, of inspired aerodynamic concepts, as well as visions of past, present aircraft developments. We will explore the fascinations of nature, the struggle to fly and the ultimate successes of our flying machines. Man most certainly has always been fascinated, and inspired by the dream of flying by observing birds soaring in the sky and flittering from tree to tree. The British aviation pioneer Sir Hiram Maxim once wrote: "*Man is essentially a land animal and it is quite possible if Nature had not placed before him numerous examples of birds and insects that are able to fly, he would never have thought of attempting it himself*"**. Many of mans flying or gliding inventions have indeed been inspired by natures creations. We will briefly look and discuss various perspectives of the evolution Nature's flyers and the evolution of man's aircraft. An interesting view of the contrasting evolution-of-flight driving forces between nature and commercial aircraft will be introduced. We will explore many of nature's fascinating flying things including birds, insects and seeds and will also shows similarities not only between Nature's flyers and Man's flying machines, but also similarities between the driving evolutionary forces for each.**

I. Introduction

Paleoaerodynamics has been defined as a rich field imbued with a long and interesting past and an even more intriguing and hopeful future. The intriguing and hopeful will be discussed in a companion paper[1]. In this presentation we will attempt to get a glimpse of insights and observations of some fascinating aspects of birds, insects and flying seeds, of inspired aerodynamic concepts, as well as visions of past, present and future aircraft developments. We will explore the fascinations of nature, the struggle to fly and the ultimate successes of our flying machines. Man most certainly has always been fascinated, and inspired by the dream of flying by observing birds soaring in the sky and flittering from tree to tree. The British aviation pioneer Sir Hiram Maxim once wrote: *"Man is essentially a land animal and it is quite possible if Nature had not placed before him numerous examples of birds and insects that are able to fly, he would never have thought of attempting it himself"*. Many of mans flying or gliding inventions have indeed been inspired by natures creations.

II. Evolution of Evolution

Some of the key events in the evolution of the theory of evolution are shown in figure 1. The grandfather of Charles Darwin, Erasmus Darwin had published in his book "Zoonomia" in 1795 early thoughts on the origin of life. Erasmus Darwin wrote that warm-blooded creatures developed from *"one living filament" and acquired new parts "in response to stimuli"* and that all improvements were inherited by successive generations.

Jean-Baptiste Lamark in 1809, published his beliefs on the origin of life in "Philosophie Zoologique". Lamarck incorporated two ideas into his theory of evolution that in his day were generally considered true. Lamark believed that individuals develop characteristics that are useful in response to specific needs and these characteristics were

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retained by usage. He also believed that individuals lose characteristics that they do not require (or use). Subsequent generations were thought to inherit all acquired traits. These unique beliefs of Lamark were ultimately disproved.

Charles Darwin published the “Origin of Species” in 1859 in which he defined that the process of “natural selection”, (which is commonly called the survival of the fittest), occurring over millions of years has resulted in all the species of life. This is generally considered to be one of the greatest scientific discoveries of all time[2]. It was once stated that “*never has so much knowledge been based on so little facts*”.

Gregor Mendel defined the statistical laws of inheritance and is considered the father of modern genetics. The notion of a gene has evolved with the science of genetics, which began when Gregor Mendel noticed that biological variations are inherited from parent organisms as specific, discrete traits. The biological entity responsible for defining traits was termed a gene. Prior to Mendel's work, the dominant theory of heredity was one of blending inheritance, which proposes that the traits of the parents blend or mix in a smooth, continuous gradient in the offspring.

Thomas Morgan (1912c) identified that genes carried on chromosomes defined the mechanical basis of heredity. He is generally considered to be the father of the modern science of genetics. The biological basis for inheritance remained unknown until DNA was identified as the genetic material in the 1940s. DNA not only confirmed the reality of evolution, it also showed at the most basic level how it reshapes living things. All organisms have many genes corresponding to many different biological traits. In cells, a gene is a portion of DNA that contains both "coding" sequences that determine what the gene does, and "non-coding" sequences that determine when the gene is active (expressed).

James Watson and Francis Crick in 1953, defined the double helix structure of DNA. This discovery unlocked the mystery of how genetic information is passed from one generation to the next[3].

Research studies by Peter and Rosemary Grant, (1970c) demonstrated that natural selection can cause evolutionary change in real time rather than only over thousands of years as Darwin had believed. More recent studies have shown evolution works not just by changing genes, but by modifying the way those genes are turned on and off by a “genetic switch”. It therefore appears that the primary source for evolution turns out not to be gene changes but changes in the regulation of genes that control development. For example, a giraffe does not have special genes to make a long neck. Its neck growing genes are the same as those for a mouse; they are just switched on for a longer time.

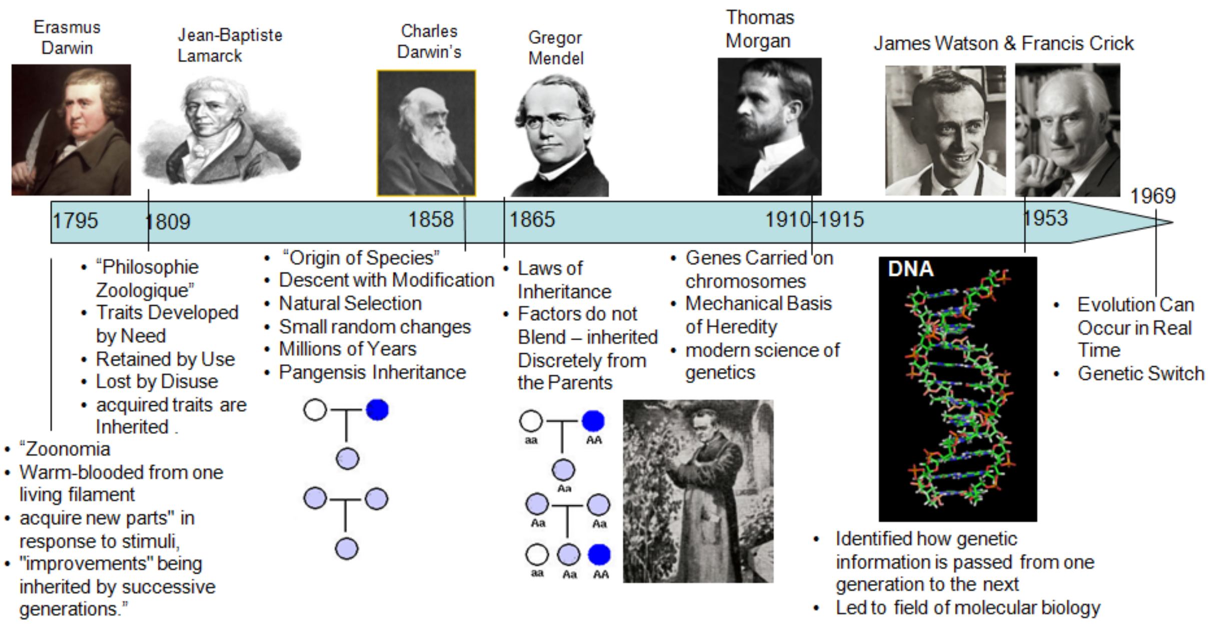


Fig. 1. Evolution of Evolution

Mice and humans (indeed, most or all mammals including dogs, cats, rabbits, monkeys, and apes) have approximately 24000 genes. In addition many of the same genes control similar functions on the different species.

The current understanding of the evolution of life indicates that four conditions must be met in order for a species to exist[4]:

- It must work mechanically and chemically
- It must be capable of being coded
- It must be able to survive at all stages of growth
- Its design must be able to be evolved through a series of forms from some other existing form, Each form being viable in its own niche of the niche wise progression

The process of evolution can be described as a gradual unrelenting improvement of living systems in response to local environmental conditions. The process of evolution in contrast to man's technology developments, does not "design" by working to specific goals or objectives, instead, evolution blindly cobbles together myriad random experiments over thousand of generations resulting in wonderfully elegant organisms whose goal is to stay alive long enough to produce the next generation which then launch the next round of random experiments[5].

The nature of the evolutionary processes of biological systems is fundamentally limiting since every new feature must develop from an existing feature. Consequently, there is no chance of making the sudden great revolutionary technology developments that are so common in the history of technology[5].

The catalyst for evolution is scarcity or limited supplies which ultimately occurs as numerical growth of a species will ultimately exceed the local resources. An advantage is an advantage only if there is an advantage for having the advantage[6].

III. COEVOLUTION

Coevolution is one of the most powerful driving forces in evolution. Coevolution involves the joint evolution of two or more species as a consequence of their ecological interaction. Each species in a coevolutionary relationship exerts strong selective pressures on the other, thereby affecting each other's evolution. The close, prolonged association between two or more different organisms of different species that may, but does not necessarily, benefit each member is called symbiosis. The major types of co-evolutionary relationships include:

1. Mutualism which is a cooperative coevolutionary symboitic relationship in which both species benefit.
2. Predation which is a competitive coevolutionary relationship between a predator and its prey.
3. Amensalism which is a symbiotic coevolutionary relationship between organisms in which one species is harmed or inhibited and the other species is unaffected.
4. Commensalism which is a symbiotic coevolutionary relationship between two species in which one derives some benefit while the other is unaffected.

Examples of two types of mutualism relationships are shown in the figure 2. Bumblebees as well as hummingbirds both obtain nourishment from flowers and various trees and in the process they spread pollen to other trees and flowers. This is an example of a service-resource relationship. An example of a service – service symbiosis is the relationship between clownfish that dwell among the stinging tentacles of sea anemones without being harmed. The anemone therefore protects clownfish from larger predators and at the same time the clownfish protect the anemones from the butterfly fish which otherwise would destroy them.

Fig. 2. Examples of Mutualism Coevolutionary Relationships

Aposematism which is most commonly known in the context of warning coloration describes anti-predator adaptations where a warning signal of potential danger or discomfort associated with the potential prey to its potential predators. It is one form of natures "advertising" signals, with many others existing such as the bright colors of flowers which lure pollinators. The warning signal may take the form of conspicuous colors, sounds, odors or other perceivable characteristics. Aposematic signals are beneficial for both the predator and prey, who both avoid potential harm. As shown in figure 3, aposematic evolutionary developments can occur in many species of mammals, insects, reptiles and fish.

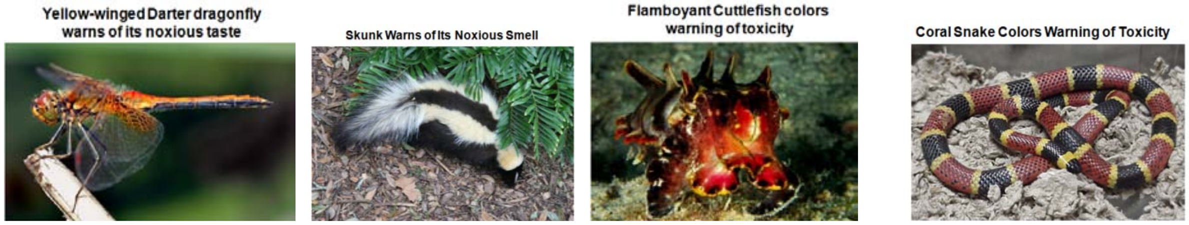


Fig. 3. Examples of Mutualism Aposematic Type of Signals

The bright colors of the yellow-winged darter dragonfly warns birds and other predators of its noxious taste. The contrasting black and white colors the skunk warns other animals and humans of its noxious smell. The bright colors of the cuttlefish and coral snake warn of their toxicity. Figure 4 shows additional examples of aposematic mutualistic developments in nature. The yellow jacket and the bumble both have highly visible yellow and black colorings to warn predators of their painful stings. The color patterns that each has evolved are very similar. This is an example of Mullerian mimicry and benefits both species by reducing the educational "cost" for each species to "teach" potential predators of their painful stings.

The harmless and palatable hoverflies and wasp beetles have evolved very similar color patterns to exploit the aposematic protection proved by the color patterns of the yellow jacket and the bumblebee. These are examples of Batesian mimicry.

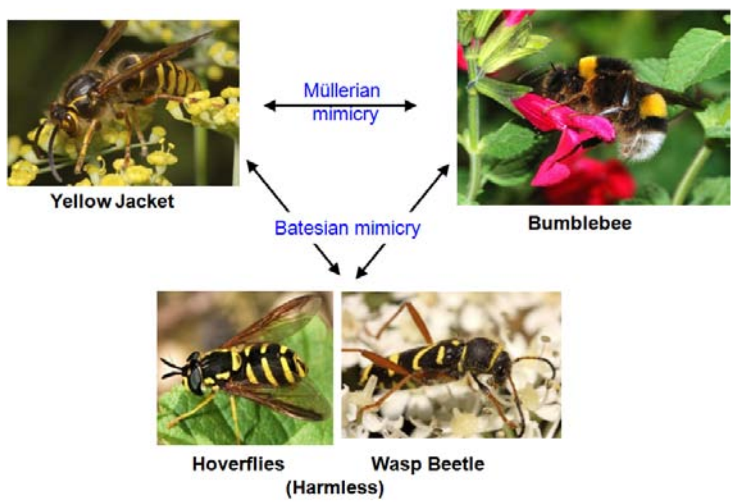


Fig.4. Mimicry in Nature ➔ Mutualism

In nature, there is a strong evolutionary pressure for animals to blend into their environment or conceal their shape; for prey animals to avoid predators and for predators to be able to sneak up on prey. Natural camouflage is one method that animals use to meet these. There are a number of methods of doing so. One is for the animal to blend in with its surroundings, while another is for the animal to disguise itself as something uninteresting or something dangerous. Examples of predator and prey camouflage patterns that have evolved are shown in figure 5.

Fig. 5. Camouflage ➔ Coevolutionary Predation Examples

Coevolutionary develops of bats and moths are shown in figure 6. Bats love moths and have developed echolocation as a means to locate and capture moths. Moths in turn have subsequently developed soft coverings to absorb the bat chirps and eliminate to some degree the benefits of echolocation. The bats then developed new chirp frequencies to be able to locate moths even with the soft coverings. The moths responded by developing enhanced stealth characteristics together with jamming techniques with their own bug chirps and new evasive maneuvers. Bats subsequently developed new elaborate flight paths and the ability to turn their chirps on and off, to confuse the moths. The arms race continues.

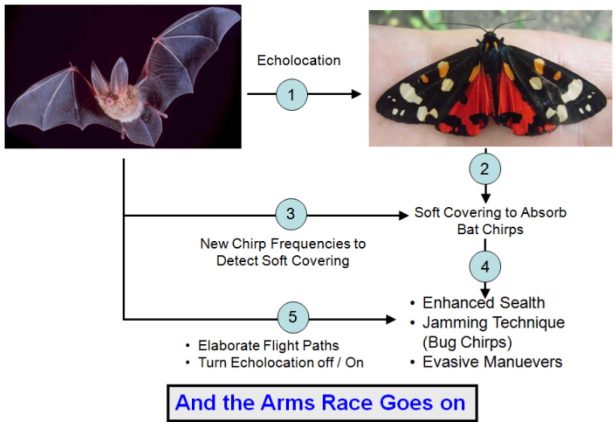


Fig.6. Coevolutionary Developments of Bats and Moths

Competition occurs when two species each require a resource that is in short supply, so that the availability of the resource to one species is negatively influenced by the presence of the other species. It is a "-/-" interaction. Competition can occur between individuals that are members of the same species. This is called intraspecific competition. Examples of intraspecific competition are shown in figure 7.

Fig. 7: Examples of Intraspecific Competetion

These examples include two bull elk competing for breeding rights and two anemones competing for growing space.

Interspecific competition occurs between members of different species. Two examples of interspecific competition are shown in figure 8. These include the lion and leopard competing for the same prey, and the water buffalo and the rhinoceros competing for the same waterhole.

Fig. 8: Examples of Interspecific Competition

There is an important evolutionary principle in nature called the competitive exclusion principle that states that: "*no two species with similar requirements can long occupy the same niche (coexist)*". The niche of a species includes all aspects of its habitat, how it makes a living, and the physical environment in which it is found. One of the species will either:

- Cease to exist
- Move from the niche of the stronger species
- Change its requirements within the original niche

It will be shown further in this report, that the competitive exclusion principle applies equally well to the development and success of both commercial and military aircraft.

IV. EVOLUTION OF NATURES FLYERS

The evolution of flight in animals and in man's flying vehicles as shown in figure 9 has steadily progressed over a period of time of approximately 330 millions of years starting with the first winged insects[7]. Pterosaurs followed nearly 140 millions of years later. The earliest bird like animals first appeared 150 millions ago followed by early flowering plants many of which have exploited flight like mechanisms to disperse their seeds. Modern insect orders, modern bird orders and bats made their appearance about 55 to 75 millions of years ago. This corresponds to the Cretaceous /Tertiary Mass Extinction Event which occurred approximately 65 millions of years ago. Successful powered flight by man has existed over a minuscule period of slightly more than 100 years.

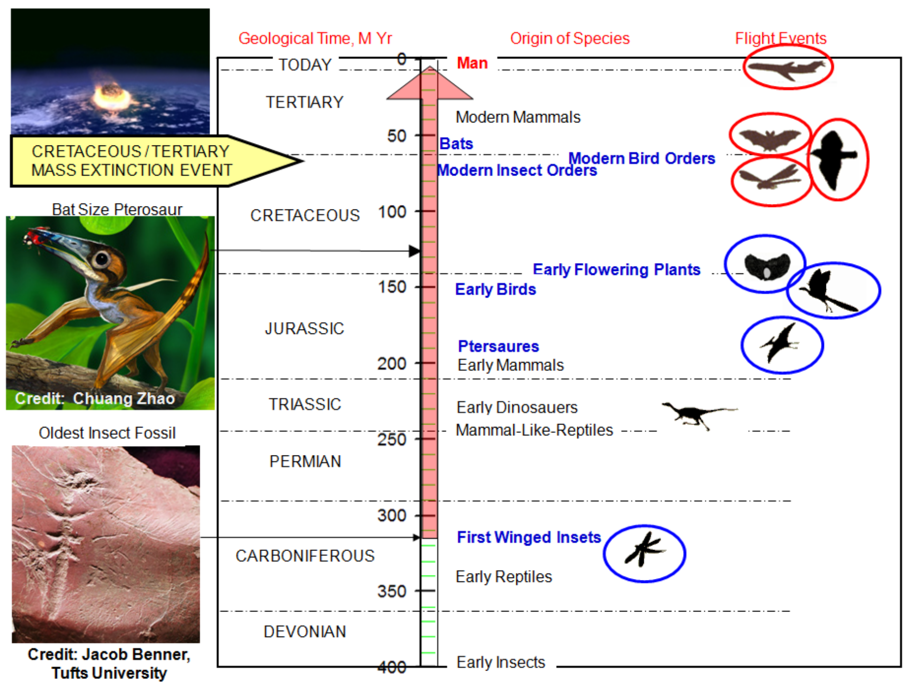


Fig. 9. Evolution of Flight

Flight is one of the most demanding adaptations found in nature because of the physical challenges of moving in air under the persistent influence of gravity. Therefore flyers in nature have been subjected to strong selection for optimum morphology. Nature's flyers as well as man's air vehicles can be described fundamentally as systems of systems. Major subsystems such as aerodynamic, structures, flight controls, "propulsion", "mechanical", "navigational", "fuel" systems, "air conditioning", and "safety / security" systems inherent in man's flight vehicles have parallels within Nature's flyers.

There exist strong synergisms between all of the functionally interdependent component subsystems. Prior developments in one subsystem are often both enabling and necessary for subsequent advancements in other subsystems. Consequently “technology” advancements in Natures flyers and in aircraft include by necessity include multiple sequenced and serendipitous developments. The “survival of the fittest” selection process for nature implies that each subsystem is in itself an optimum solution within the confines of the overall optimized system.

Nature has evolved four convergent solutions for the challenge of flight. These include birds, bats, pterosaurs and insects all of whose wing structures are shown in figure 10.

Bats, birds, and pterodactyl wings not only perform the same function of providing the means of flight, but they are also examples of homologous structures since the limbs of all these organisms contain many of the same sets of bones. These have been passed downed to all these different animals from a common ancestor. These wings are also homologous to the human arm and hand. They all contain a sternum, clavicle, scapula, humerus, ulna, radius and digits.

The wings of insects are analogous structures relative to the other previously discussed wings because of the fundamental differences in their internal anatomy even though they perform the similar function of flight.

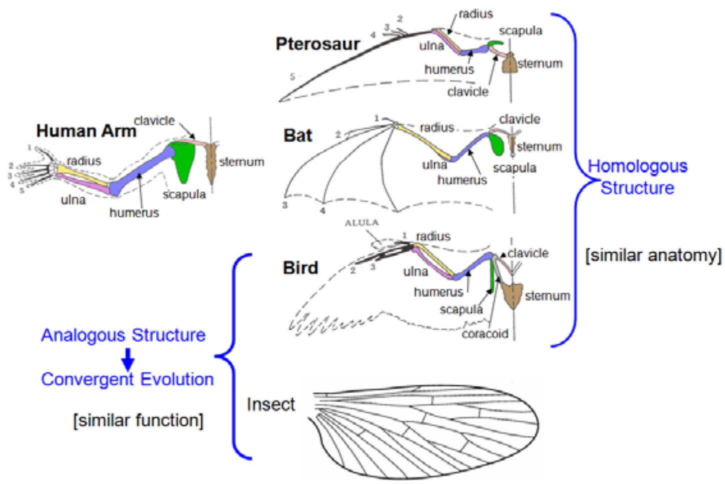


Fig. 10. Natures Wing Designs

The design of an insect wing at first glance would appear to be very complex. The basic design is however rather simple and extremely elegant. The wings of the dragon fly are strengthened by a number of longitudinal veins which have cross connections that form closed cells in the membrane. The patterns that result from the fusions and cross connection of the wing veins are often diagnostic for different evolutionary lineages and can be used for identification of the family level in many orders of Insects. The general design of the wing can be understood by applying the simple intersecting membrane sketches shown in figure 11.

In these sketches, two large parallel membranes with tension “T”, are joined by a crossing membrane with tension “t”. In Sketch “A” the tension “T” in the large veins is much larger than tension “t” in the cross membrane. The cross membrane therefore intersects the large membrane at a 90^{O} angle.

In Sketch “B” the tension “T” in the large veins is only slightly larger than tension “t” in the cross membrane. The cross membrane therefore pulls the large membranes in slightly such that the intersection angle is approximately 100^{O} to110^{O} .

In Sketch “C” the tension “T” in the large veins is equal to the tension “t” in the cross membrane. The cross membrane therefore pulls in the large membranes so that the intersection anglel is approximately 120^{O}.

We can now define the basic design of the by four simple rules:

1. Main Veins tend to run parallel out the wing
2. When two large veins are so near that only 1 Cell is between, the Cells are quadrangles with the thin partitions intersecting the sides at right angles
3. With 2 cells between ribs, Cells fit each other with 120^{O} angles and meet the ribs at right angles (pentagons)
4. With many cells between ribs, all angles in common tend to be 120^{O} (hexagons)

As shown in the figure, these four rules do indeed define the general characteristics of the structure of the dragon fly wing.

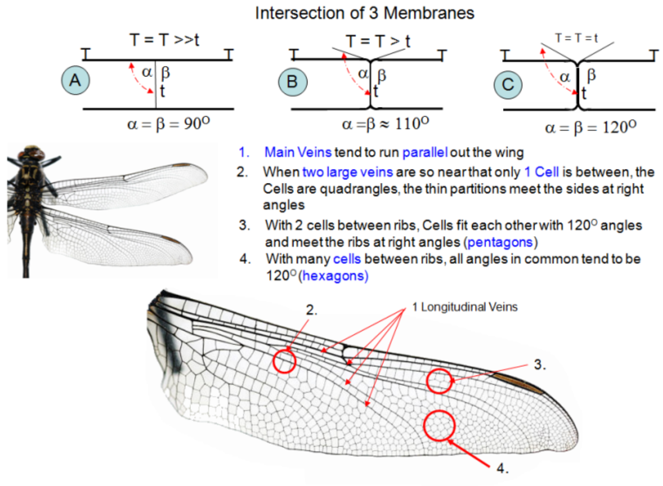


Fig. 11. Elegant Design of an Insect Wing

Other natural fliers include the seeds of wind pollinating plants that evolved to provide their parent species one of the most remarkable and effective of all seed dispersal methods, riding the wind and air currents of the world[8]. Some common examples are the milkweed seed, which may be considered a direct natural antecedent of the parachute, and the maple seed, a natural prototype of the autogyro. Of considerable historical interest, because it demonstrated to aviation pioneers the feasibility of constructing a true self- stable tailless airplane, is the gliding seed of the Java palm tree, zanonia macrocarpa.

Although winged insects were the first creatures to fly, our subsequent discussions will primarily focus on the developments of the flying capabilities of birds.

Flight capability opened up new sources of food, made escape from earthbound predators easier and increased the safety of living and breeding quarters. Impenetrable barriers such as mountains, oceans or rivers became easily navigable. Ultimately flight made it possible to follow favorable climates and changing food sources by means of seasonal migrations.

Probable steps in the evolution of flight in birds are shown in figure 12.

Locomotion	Goal	Adaptations	Nature's "Technology" Achievements
1. Climbing [running}	Foraging and avoiding predators	Climbing agility [running agility]	Survival
2. Parachuting (steep gliding); [hang-gliding]	More effective foraging and avoiding predators	Larger forearm surface (propatagium, feathers)	
3. Gliding	Optimal foraging, movements between foraging areas	Larger wings, lower wing loading	
4. Gliding with some maneuverability	Ability to determine direction of the glide	Neuromuscular control, wing coordination, wing camber	Efficiency
5. Slight flapping flight	Movements for stability, maneuvers in turning and landing	Higher aspect ratio, lower wing loading	
6. Flapping flight with some maneuverability	Better flight performance, commuting	Better neuromuscular control, more sophisticated wing features, camber for slow flight	Functionality
7. Flapping flight with high maneuverability , Soaring	Aerial prey-capturing, hovering etc. Soaring /Migration	Highly sophisticated wing features, slots, keeled sternum, musculoskeletal system like that of modern birds	Higher, Faster Farther

Fig. 12. Probable Steps in the Evolution of Avian Flight Capability

The initial steps in the evolution of flight were fundamentally driven by the needs of *survival*. These needs included safety from predators for both the individual and their offspring and more effective means of foraging. The early flight capabilities included parachuting and rudimentary gliding abilities. The enabling anatomical changes included developing the fundamental structure of the wing including the incredible concept of the feather.

The next series of steps in the march of evolution of flight provided more *efficient* gliding flight with some maneuverability and the initiation of slight flapping flight. These provided the ability to determine the direction of the glide and stabilizing movements for turning and landing. The anatomical changes included development of neuromuscular control for coordination of wing movements and more effective wing geometry shapes.

Subsequently evolutionary developments provided increased flight *functionality* and better flapping flight performance with some degree of maneuverability. The associated anatomical developments included better neuromuscular control and more sophisticated wing aerodynamic characteristics.

The next category of evolutionary steps for avian flight provided the ability to fly "higher, faster and farther" by providing flapping flight with high maneuverability soaring and hovering capabilities.

The varied developments of the eyes of predator birds and the eyes of birds that are the targeted prey as shown in figure 13 are an example of avian co-evolutionary developments. Most birds cannot move their eyes. Prey type birds have eyes located on the sides of their heads which results in a wide field of vision which is extremely important for detecting any approaching predators. Predator type birds such as the owl have their eyes located on the front of their heads which provides binocular vision for accurately estimating distances to a prey when hunting.

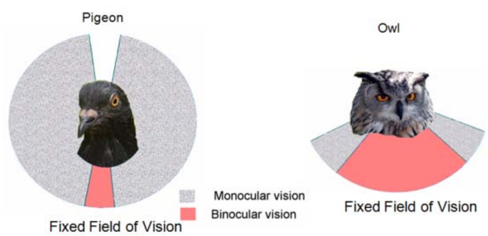


Fig. 13. Co-Evolutionary Development of Vision and Eye Structure ➔ Predator vs. Prey

Many avian species focus on distant objects preferentially with their lateral monocular field of vision. Consequently, birds will position themselves sideways to maximize visual resolution. For a pigeon, resolution is twice as good with sideways monocular vision as with forward binocular vision, whereas for humans the converse is true. When a prey type bird turns their head away from an object they are doing so to obtain a more accurate view.

Nature’s flyers as well as man’s air vehicles can be described fundamentally as systems of systems. Many of the major subsystems such as aerodynamic, structures, flight controls, “propulsion”, “mechanical”, “navigational”, “fuel” systems, “air conditioning”, and “safety / security” systems inherent in man’s flight vehicles have parallels within Nature’s flyers. There exists strong synergism between all of the functionally interdependent component subsystems. Prior developments in one subsystem are often both enabling and necessary for subsequent advancements in other subsystems. Consequently “technology” advancements in Natures flyers and in aircraft include by necessity multiple sequenced and serendipitous developments.

The unending process of evolution driven by the “survival of the fittest” is molded by local environmental effects and the demands of co-evolution including both responsive developments and those that provide competitive advantages. Consequently nature has produced many unique acceptable flying designs as evident in the approximately 8000 bird species, 1000 species of bats and 350,000 species of flying insects.

Figure 14 shows how the local environmental effects have shaped the bills of many species of birds as a result of different feeding adaptations.

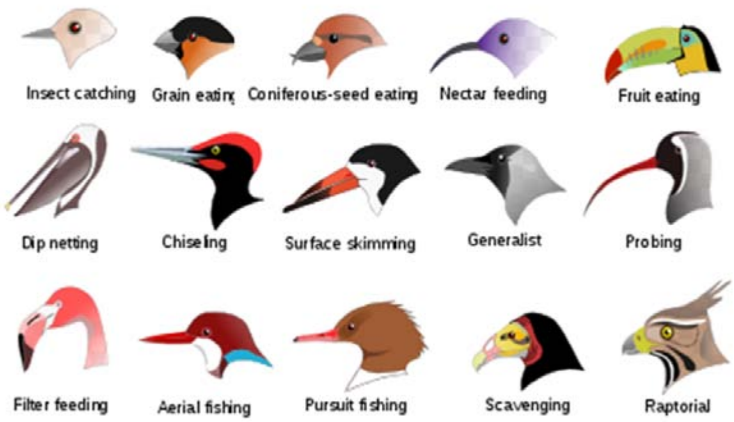


Fig. 14. Effect of Different Feeding Adaptations on the shape of Bird Bills.

Birds are dramatically different from all other living creatures. Feathers, toothless beaks, hollow bones, perching feet, wishbones, deep breast bones and stump like tailbones are only part of the combination of skeletal features that no other living animal has in common with them.

Figure 15 shows various systems of systems developments in the evolution of birds. The developments or adaptations that are shown in the figure are grouped according to:

- Weight-reducing adaptations
- Power-increasing adaptations
- Aerodynamic adaptations

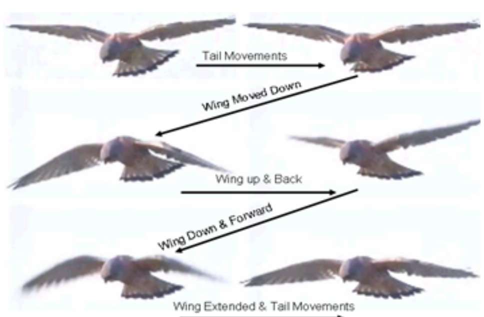
Weight-Reducing Developments
Thin, hollow bones
Light feathers
Elimination of teeth and heavy jaws
Development of the beak
Gizzard for grinding food
Elimination of bladder
Extensive bone fusion
Local Region Adaptions
"Self healing" design philosophy

Power-Increasing Developments
Warm-blooded
Heat-conserving plumage
Energy rich diet
Branching air sacs (Supercharger)
Rapid circulation
Large 4 chamber heart
High blood sugar levels
Breathing synchronized with wing beats
High rate of metabolism

Aerodynamic Developments
Development of forelimb as a wing
Wing integrated Feather Design
Infinitely variable morphing wing
Streamline bodies and Wing Airfoil shapes
Flow control adaptations
Control device (eg, Tail, Tip Feathers, etc.)
Flight Critical Stability System

Fig. 15. System of System Adaptations in the Evolution of Birds

The pictures in figure 16 which were taken from the outstanding video by Gareth Jones[9], show a kestrel, which is a small hawk, hovering on up flow air currents on the windward side of a steep hill. Even though the air currents are moderately gusty, the kestrel is able to keep its eyes and head position remarkably fixed in space allowing continual and total focus on its potential prey[9].



Picture Credit: Gareth Jones, betacygni @ Youtube, Used With Permission

Fig. 16. Hovering Kestrel Demonstrating Structural and Neuromuscular Control

This is an excellent example of the impact of a bird's evolutionary structural and neuromuscular control adaptations and the resulting wing and tail movements some of which include:

- Pitch Stability and Control
  - A long, sturdy, movable flattened tail (e.g. Archaeopteryx)
  - Downward and upward movements of the tail
  - Fore and aft movements of the wing relative to the center of gravity
- Roll Stability and Control
  - Long, broad wings with rounded tips
  - Sweepback
  - Wing asymmetric dihedral like movements
  - Twisting the wings in different directions
- Yaw Stability and Control
  - Long, broad wings with rounded tips
  - Tail rotary movements
  - twisting And flexing the wings to change drag

In the vernacular of an aerodynamicist, the Kestrel hovering flight demonstrates a highly sophisticated flight critical dynamic morphing coupled aeroservoelastic control system.

The kestrel also provides a powerful message for success: *"Keep Your Eye upon Your Goal"*

V. SPECIAL NOISE REDUCING FEATURES OF AN OWL

The special noise reducing features of an owl are another example of evolutionary systems integration in nature. Much of the owl's hunting strategy depends on stealth and surprise. Owls as shown in figure 17, have many evolutionary adaptations that aid them in rightfully achieving the reputation as nature's master of stealth.

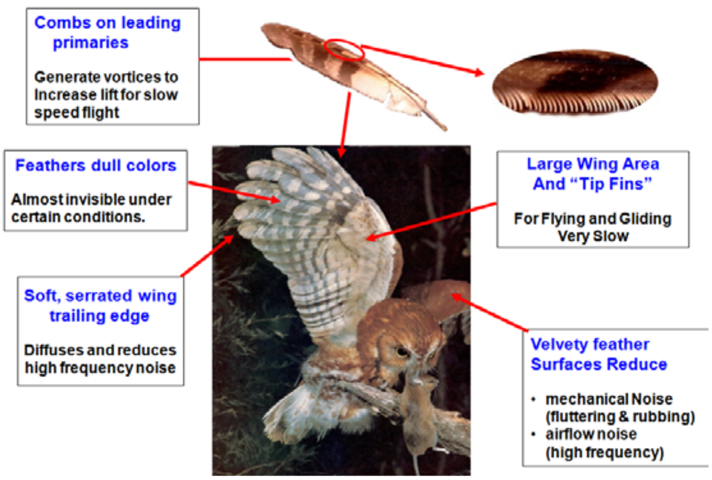


Fig. 17. Noise Reducing Features of an Owl

The owl has a large wing area and "tip fin" feathers for flying and gliding slowly. The wings are covered by velvety feathers to reduce mechanical noise due to fluttering, flapping and rubbing. This surface also tends to reduce high frequency airflow noise. The soft serrated wing trailing edge muffle the owl's wing beats, allowing its flight to be practically silent. The combs on the leading edge of the primary feathers generate vortices to increase lift for slow speed flight. The dull colors of the feathers on the lower surface make the owl almost invisible under certain conditions.

The silent flight characteristics of the owl as shown in figure 18 have two objectives. The obvious first objective is to avoid detection by the potential prey. The second and equally important objective is to enable the owl to detect the quiet noise levels such as mouse squeaks and leaf rattles.

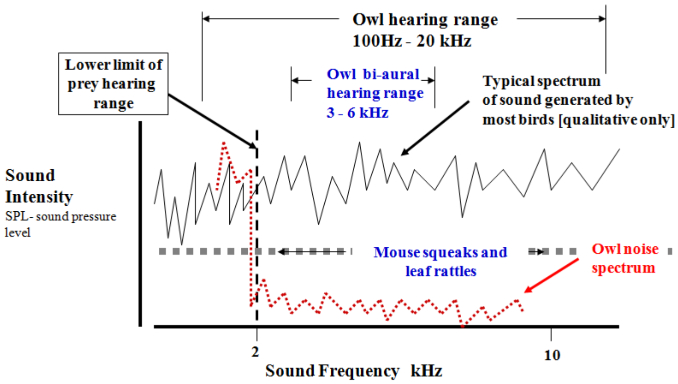


Fig. 18. The "Silent" Flight of Owls

Owls as shown in figure 19 have a highly effective detection system for locating their prey.

Fig.19. Integrated Detection System

Owls have spectacular binocular vision allowing them to pinpoint prey and see in low light. The eyes of Great Horned Owls are nearly as large as those of humans and are immobile within their circular bone sockets. Instead of turning their eyes, they turn their heads a full 270 degrees in order to see in other directions without moving its entire body. The very large eyes are packed with light sensitive rods and are about 100 times more sensitive in low light than ours. They can see an object a mile away at night lit by a candle. Owls are very near sighted and are unable to see within a couple of inches. Consequently owls have sensitive filoplumes on the feet and beak which act as feelers.

An owl's hearing is as good – if not better – than its vision; they have better depth perception and better perception of sound elevation (up-down direction) than humans. This is due to owl ears not being placed in the same position on either side of their head: the right ear is typically set higher in the skull and at a slightly different angle. By tilting or turning its head until the sound is the same in each ear, an owl can pinpoint both the horizontal and vertical direction of a sound. The facial disc helps to funnel the sound of prey to their ears. In many species, these are placed asymmetrically, for better directional location.

VI. EVOLUTION OF TECHNICAL FLIGHT

It is well documented[11, 12, 13, 14, 15] that the more successful of the earlier pioneers of manned flight were inspired by natures flying creatures and objects and were well versed in the then current understanding of flight mechanics.

"Of all animal movements, flight is indisputably the finest. It may be regarded as the poetry of motion. The fact that a creature as heavy, bulk for bulk, as many solid substances, can by the unaided movements of its wings urge itself through the air with a speed little short of a cannon-ball, fills the mind with wonder".

The concept that the inspiration of natures flyers lead to experimentation, then the realization of manned flight and ultimately leading to the proliferation of flight capabilities through many airplane concepts is often the traditional view of the history of flight. However a more expanded view of the history of flight is shown in figure 20. Nature's evolutionary processes and man's technology development are all bound together by the underlying requirements that each must obey the same fundamental laws of physics, chemistry - and economics. However the evolutionary processes of biological flight are significantly different than the evolutionary processes of technical flight although as will be shown later, many of the co-evolutionary symbiotic relationships are, however, quite similar.

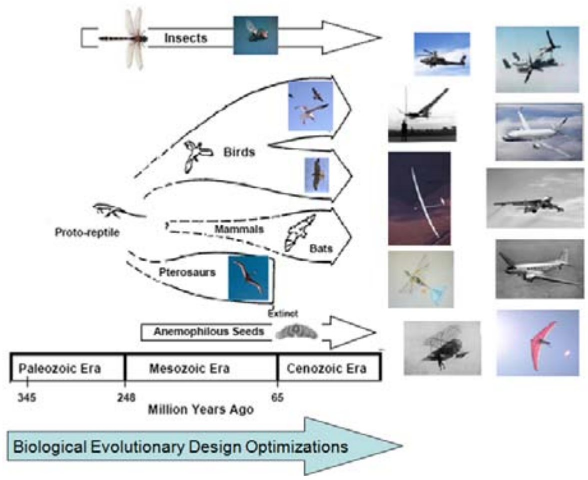


Fig. 20. View of the Evolution of Flight

A more expanded view of the evolution of flight is shown in figure 21 to highlight the fact that Man's desires, thoughts, and efforts to fly have occurred not just over the past "Century of Flight", but over a period of hundreds of years. As it will be shown, this evolutionary period was highlighted by the enhancement our Knowledge of Flight Dynamics (KFD), our Understanding of Flight Dynamics, (UFD) plus the sequential developments of critical and necessary supporting technologies.

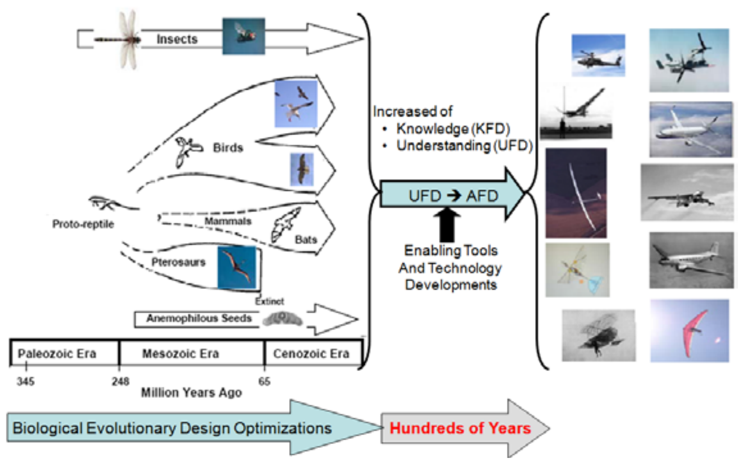


Fig. 21. Expanded View of the Evolution of Flight

The initial tools that were available to the early pioneers of flight are shown in figure 22. These include the information, ideas and interpretations that they gleaned from observations of birds soaring, bats flying and Hummingbirds hovering. We call this Visual Flight Dynamics, VFD. Otto Lilienthal (circa 1890) who is considered by many to be the pioneering father of flight stated "*In order to discover the principles which facilitate flight, and to eventually enable man to fly, we must take the bird for our model*."

This visual information formed the basis of their Knowledge of Flight Dynamics (KFD) from which they formalized their Understanding of Flight Dynamics, (UFD). It should be noted that knowledge and understanding are not the same, nor is all knowledge absolute, accurate or factual.

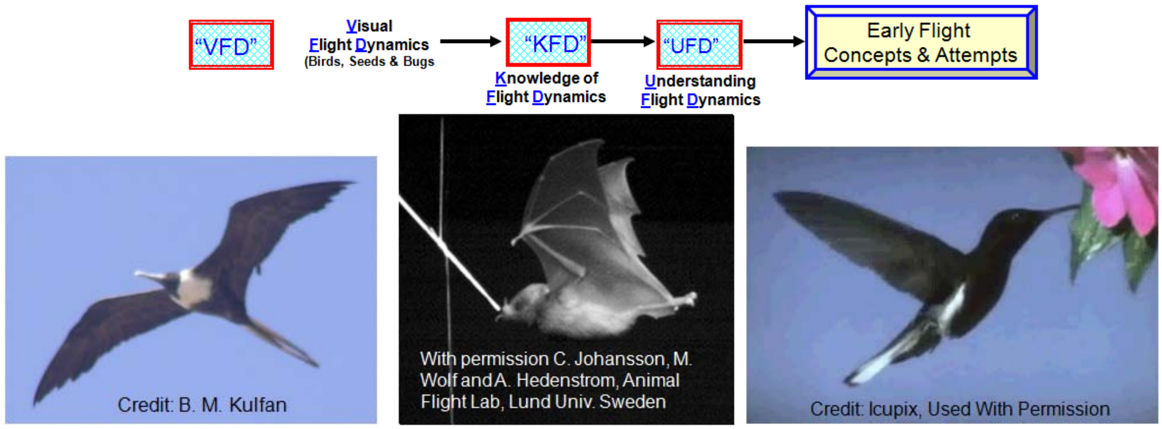


Figure 22: Early Aerodynamic Tools

The longing to fly like a bird that man has long endured is typified by the passionate words of Otto Lilienthal (c 1892): "*With each advent of spring, when the air is alive with innumerable happy creatures ---- then a certain desire takes possession of man. He longs to soar upward and to glide, free as the bird, over smiling fields, leafy woods and mirror like lakes, and so enjoy the varying landscape as fully as only a bird can do.*" Lilienthal with great perceived emotion also said "*The observation of nature constantly revives the conviction that flight cannot and will not be denied to man forever.*[14]"

VII. EARLY UNDERSTANDINGS OF AVIAN FLIGHT

It is interesting to examine the details of the state of knowledge of the physics of bird flight as recorded in books that were published in the time period of the Wright Brothers initial flights[12, 13, 14, 15]. Man's concepts of the nature and the physics of avian flight gradually developed from endless hours of observing the flight of birds over centuries of time. This source of "technical" information is called VFD (visual flight dynamics). Early observations such as shown in figure 22 formed the basis of the evolving knowledge of flight dynamics, KFD and the understanding, UFD (not necessarily correct) of flight dynamics that ultimately led to man's initial attempts to fly.

One of the earliest recorded pictures of the observed nature of flight is shown in figure 23. This is a cave painting from about 11,000 years ago, of what appears to be a bird landing. The picture suggests that the artist had a rather accurate understanding of the use of wings during landing, including what appears to be the extended alula[11].

Fig. 23. Earliest Known Cave Painting of a Bird.

DaVinci's well known sketches of bird flight from about 1500 are shown in figure 24. These sketches also show his interpretation of the characteristics of the flow around the bird. The third daVinci picture shows the tail being deflected as a stabilizing mechanism. It is generally believed that these sketches were based more on his understanding of the physics of flight that on any particular flight observation.

The sketches by Borelli shown in figure 19, illustrate his concept of the manner by which birds fly as he stated in his masterpiece "De Motu Animalium" that appeared after his death in about 1680. "*Birds fly by beating the air with their wings. They jump as it were through the air just as a person can jump on the ground ------ Wing beats compress the air and the air bounces back.*" Borelli's understanding that the tail moved up and down to provide pitch control differed from the previously accepted belief advocated by Aristotle, that the tail acted as a rudder. Borelli also stated that birds change their horizontal direction by beating the left and right wings at different speeds similar the way that a “*rower alters course by pulling harder on one oar than the other*”.

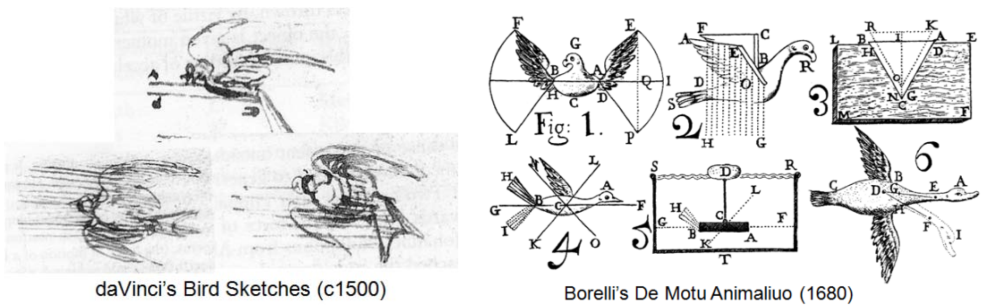


Fig. 24. Early Interpretations of the Nature and Mechanisms of Avian Flight

The explanation of the mechanics of avian bird flight defined by Borelli was accepted as being scientifically correct for nearly 200 years. Pettigrew in his book ANIMAL LOCOMOTION or WALKING, SWIMMING, AND FLYING, WITH A DISSERTATION ON AERONAUTICS[12], which was published in 1873, wrote: *"With regard to the production of flight by the flapping of wings,----- De Motu Animalium of Borelli, published as far back as 1680, i.e. nearly two centuries ago. Indeed it will not be too much to affirm, that to this distinguished physiologist and mathematician belongs almost all the knowledge we possessed of (flapping) wings up till 1865.”*

A very significant supporting technology development that provided valuable insight into the nature of flight was the chronophotographic gun that Etienne-Jules Marey[15] perfected in 1882. With this instrument Marey was capable of taking 12 consecutive frames a second, and the most interesting fact is that all the frames were recorded on the same picture as shown in figure 25. With this instrument, it was then possible to observe the intricate motions of a bird or insect in flight. Marley’s photographs were an early form of Visual Flight Dynamics, VFD.

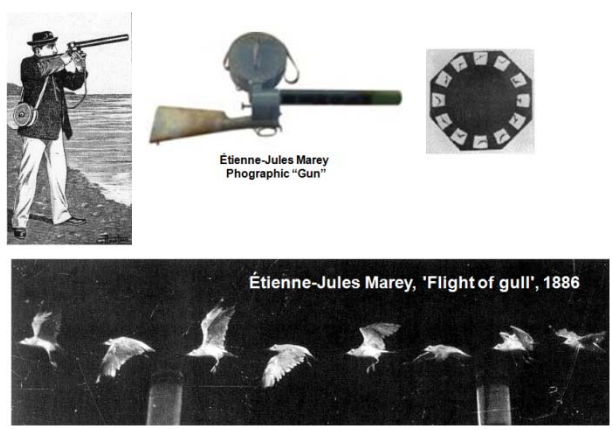


Fig. 25. Marey’s”photographic gun” capable of taking twelve exposures in one second. (1882)

Marley also made movies at high speed (60 frames per second). He is widely considered to be a pioneer of photography and an influential pioneer of the history of cinema. During the 1860s Marey focused on the study of flight, first of insects and then birds. His aim was to understand how a wing interacted with the air to cause the animal to move. He also devised some ingenious apparatuses such as a corset which allowed a bird to fly around a circular track while recording the movements of its thorax and wings.

Otto Lilienthal published the results obtained by him, working in conjunction with his brother, after long years of quiet scientific study and experiment, in 188912. This book contained the “discovery” of the driving forward of arched surfaces against the wind. Lilienthal said "*The problems why a flying bird does not drop to the ground, how it is sustained in the air by an invisible force, may be considered fully solved so far as the nature of this supporting* *force is concerned."* Figure 26 contain sketches of the shapes of various bird wing geometries, plus a sketch of the details of a stork's wing. It is obvious that the Lilienthal brothers had a obtained a rather thorough understanding of the flight features of a bird.

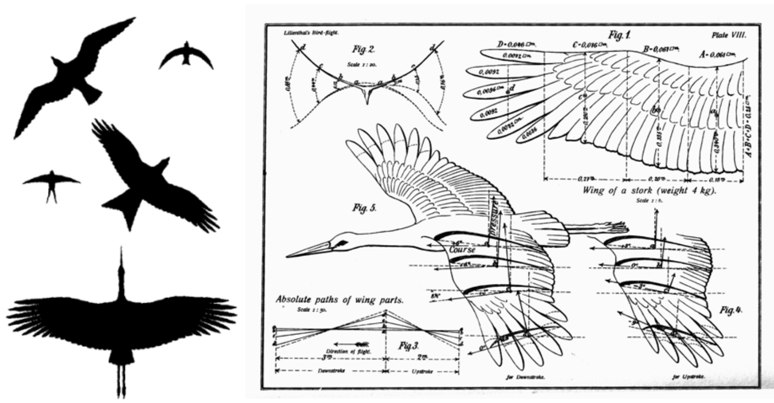


Fig. 26: The Lilienthal's Bird Flight Concepts

Five methods of bird flight were distinguished[11] in the period in which the Wright Brothers entered the scene. The first method was called "rowing flight" (corresponding to the modern day vernacular of flapping flight), was formulated by a combination of chronograph measurements together with a series of photographs. The photographs were obtained simultaneously from three directions showing the showing the movements of the wings at various sequential moments. (The early concept of early flight related the mechanics of flapping flight to the motion of rowing a boat. This is substantially different that the actual mechanics of flight.)

The second method called Gliding flight was defined as *"rowing flight interrupted by the passive flights - the gliding. During gliding the flapping of the wings is halted, and the flight is sustained by the kinetic energy generated during the rowing flight*". (This definition corresponds to our present day concept of bounding or intermittent flight).

The third method was called soaring. *"During soaring, the bird remains over a point on the ground without flapping its wings; soaring is rendered possible by upward currents of air, forming over wooded land and on rugged rocks. The activity of the muscles is confined, in this case, to feeble balancing turns of the stretched wings about the body longitudinal axis."*

The fourth method was called sailing. *"Sailing is seen frequently with sea gulls following ships or progressive waves. This movement is caused by the wind, reflected upwards after striking the sails or crests of the waves, holding the bird at a constant height and at a constant distance away from the sail or the wave crest, as the case may be. The difference between sailing and soaring is, that the animal not only remains at a constant height, but in the former case also is driven forwards."*

The fifth method was called circling. The *"explanation of the circling of birds is attended with especially great difficulties"*. Apparently the physics of thermals caused by local uneven heating of landmasses was unknown at that time. These thermals result from a central ring of revolving air with a core of rising colder air. The birds circle to remain in the core of rising air and then glide between other thermals.

It is interesting that there was no specific mention of hovering, either as a form of active flight in the case of humming birds rapidly beating their wings, or as a form of passive flight as in the case of the Kestrel riding rising upward currents over a steep hill as the previously shown in figure 16.

VIII. MAN'S EARLY FLIGHT CONCEPTS

The earliest concepts and attempts at flying were all based on attempts to directly emulate the flight of birds as shown in figure 27. Leonardo said that "*a bird is an instrument working according to a mathematical law. It lies within the power of man to make this instrument with all its motions."* Leonardo like many of the early pioneers of flight that followed, based on their observations of birds, believed that in order to fly, man would need a pair of flapping wings. These devices became known as ornithopters. DaVinci's concept of an ornithopter was developed in the 1486 to 1490 time period, However there is no evidence that he actually built or tested such a concept.

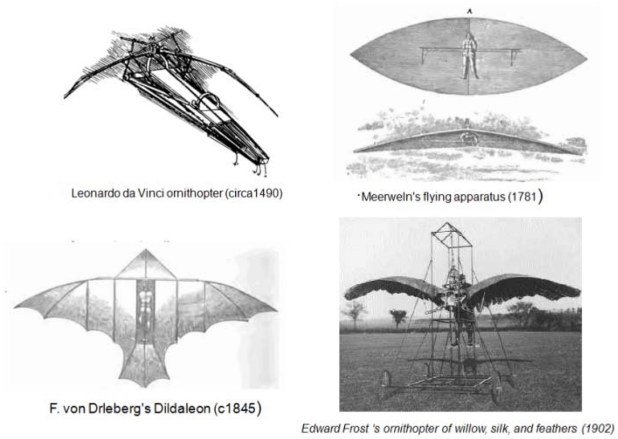


Fig. 27. Early Flapping Wing Concepts

Karl Meerwein was the first to estimate the size of a wing surface necessary to support the weight of a man using as a basis, the weight and corresponding wing area of ducks. Taking the wild duck as his model, he found that a man, weighing 200 lbs. with the machine, would require a surface of 126 sq. ft. His apparatus consisted of two light wooden frames covered with calico. The pilot was fastened in a horizontal position in the middle, with a balancing rod in front of him, which worked the strokes of the wings when pressed by the body. Meerwein apparently made one unsuccessful flight attempt in 1789.

Friedrich von Drieberg was the first to acknowledge that man has the greatest power in the muscles of the leg, and must use these for the movements of flight. Up until this time it was commonly assumed that the wings must necessarily be moved with the arms. Von Drieberg's concept consisted of a bat-like flying apparatus in which flight was to be obtained by flapping the wing by treading with the feet, while lying horizontally.

Edward Frost constructed an ornithopter made of willow, silk and feathers supported on a wooden frame. When his ornithcopter was suspended from a tree it was said that it would rise slightly with every beat of the wings. The entire contraption was much too heavy to ever fly. He built his last ornithcopter in 1904, a year after the Wright brothers first flew. Frost later became the president of the Royal Aeronautical Society.

The earliest known idea for flight with fixed wing geometry as in today's airplanes is the 1799 aircraft design by George Cayley which was sketched on a small coin. This concept is shown in the sketch on the left side of figure 28. Cayley's design had fixed wings for lift, a movable tail for control, and rows of "flappers" beneath the wings for thrust.

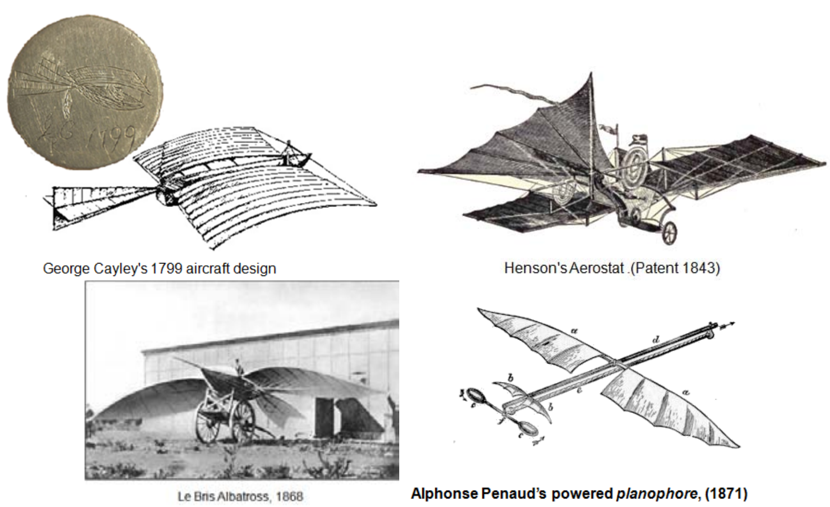


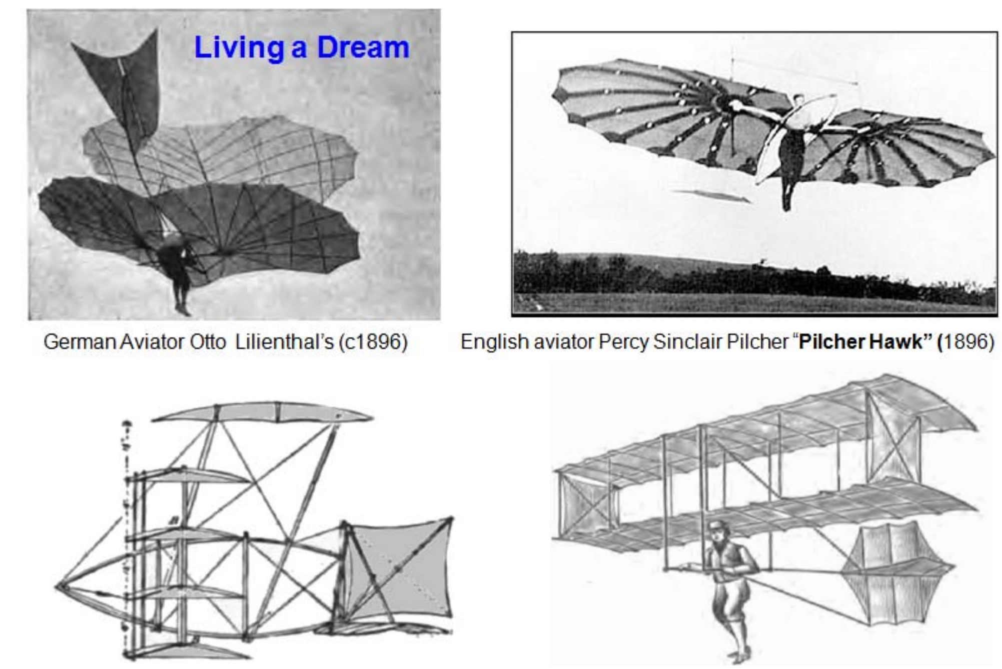
Fig. 28: Early Fixed Wing Flyers

Henson's steam powered fixed wing aircraft concept was the first patented airplane concept (1843). Alphonse Penaud in 1871 built a planophore, a 20-inch long monoplane with a pusher propeller powered by a rubber band. It flew 131 feet in 11 seconds becoming the first flight of an inherently stable aircraft. In 1874 Bishop Milton Wright bought one of Pénaud's toy helicopters. He took it home to his boys, Orville and Wilbur and, right there, Pénaud ultimately changed the course of history. While many of the early glider concepts were dangerous exercises of futility, others begin to add to the accumulation of knowledge of the critical elements for successful flight.

Le Bris built a glider shown in the middle right of figure 28, which was inspired by the shape of the Albatross. The glider consisted of a wood frame and was covered in cloth. The pilot (Le Bris) sat inside, almost like in a canoe, and used levers to operate the movements of the wings and tail. This invention which he patented in 1857, was the first flight control concept. In 1856 he briefly “flew” the glider was put on top of a cart which was attached to a horse that ran against the wind. At this point, the Artificial Albatross was released from the cart and began to rise into the air. The Albatross glider became the first ever to be photographed, albeit on the ground, by Nadar in 1868.

Figure 29 shows the pioneering aviation giants from three countries. Otto Lilienthal from Germany conducted the first extensive series of engineering type of fixed wing glider experiments. Over the period of 1891 to 1896 he conducted over 2000 gliding flights before he perished when his glider stalled and crashed from an elevation of 50 ft.

Alexander Graham Bell after observing one of Lilienthal’s gliding flight wrote: “Lilienthal boldly launched himself into the air in an apparatus of his own construction, having wings like a bird and a tail for a rudder. Without any motor, he ran down hill against the wind. Then, upon jumping into the air, he found himself supported by his apparatus, and glided downhill at an elevation of a few feet from the ground, landing safely at a considerable distance from his point of departure. This exhibition of gliding flight fairly startled the world.”



German Aviator Otto Lilienthal’s (c1896)   English aviator Percy Sinclair Pilcher “**Pilcher Hawk”** (1896)

Americam Aviator Chanute's multiple-winged machine 1896   Chanute'. double-decker (Box Wing) 1897.

Fig. 29: Early Fixed Wing Flyers -- the Aeronautics Giants

Pilcher, the English aviator, built and tested a number of glider designs between 1895 and 1899 when after a structural failure; he was killed in the collapse of his last glider. His experiments provided a series of important results:

- Too much wing dihedral reduced stability in side winds.
- Too low center of gravity makes the apparatus very difficult to control.
- A flying machine can safely be raised by towing it against the wind like a kite.
- Light wheels at the front are convenient to move the machine about and to absorb shocks in landing.

Chanute after experimenting with various mono-wing gliders, started to experiment with various multi wing concepts as shown in figure 29. The concepts were initially based on kite designs that exhibited stable flight characteristics. He ultimately ended up with his biplane box-wing concept shown in the right side of the figure.

Chanute in time became a mentor to the Wright brothers. The wing planform geometry which the Wright brothers choose for their gliders and also for the Wright flyer was very similar to Chanute's double decker box wing shown in the right of figure 29.

Professor Langley in the U.S. built a large model of an "aerodrome" driven through the air by a steam-engine under the action of its own propeIlers (figure 30). Alexander Bell was a witness of the memorable experiments made by Professor Langley on the 6th of May, 1896, with this large sized model, which had a spread of wing of about 14 feet. After observing the flight of the large model, Alexander Bell stated *"No one who witnessed the extraordinary spectacle of a steam engine flying with wings in the air, like a great soaring bird; could doubt for one moment the practicability of mechanical flight."*

Figure 30: Professor Langley's "Aerodrome"

The imaginations of the early aircraft designers were almost unlimited in scope. These early aviation pioneers studied the flight characteristics of every conceivable type of flying animal-birds, insects, bats, flying fish, even flying foxes. Figure 31 shows the Avion III which was designed in 1897 and modeled after the geometry of a bat.

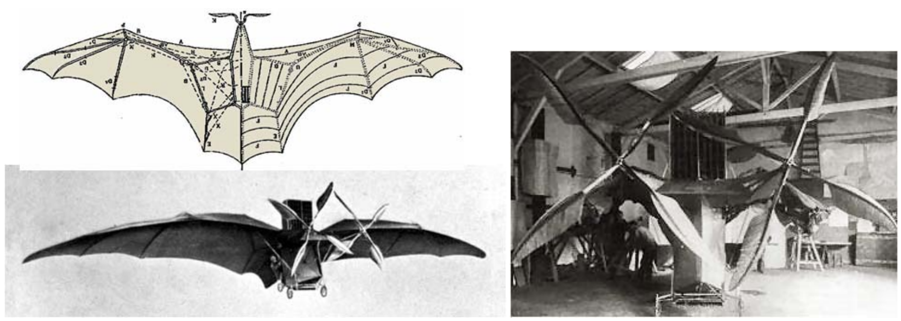


Fig. 31: Early Inspiration from a Bat

The Avion III (Éole III) was a primitive steam-powered aircraft built by Clément Ader between 1892 and 1897, financed by the French War Office. This aircraft retained the same basic bat-like configuration of an earlier aircraft, the Éole. The Avion III was equipped with two engines driving two propellers. The propellers actually had a feather like structure. The Avion was equipped with a small rudder as means of directional control. Trials of the aircraft began at the Satory army base near Versailles on October 12, 1897, with the aircraft taxiing along a circular track. The first actual flight was attempted on October 14, 1897. The flight ended almost immediately in a crash without ever leaving the ground.

IX. FLYING SEEDS

Dr. McMasters stated "*Plants mastered the art and science of aviation long before Orville and Wilbur Wright propelled their frail craft into the air"*[8]. This is evident in the concepts that nature has developed to enable seeds to navigate to suitable soil. If a tree dropped its seeds straight down, the seedlings would have to try to grow in the shade of the parent tree and would soon choke each other out. Seeds need to be carried away from its parent tree or plant and this now is accomplished in a variety of ways.

The most interesting aerodynamic example is probably the winged Zanonia macrocarpa seed shown in figure 32. This kidney-shaped seed comes from a large vine of the cucumber family. It grows in the dense, moist jungles of Indonesia and has adapted its reproductive processes to a region in which there is no wind to distribute the seeds.

The vine climbs 150-foot trees, and near the top, the Zanonia seed develops with two curved wings, transparent, gleaming, and very elastic. The seed-a kidney-shaped planform when released, begins its glide, rising on thermals from the jungle heat, and finally landing at a considerable distance from its point of departure. One professor described the Zanonia glider in this way: "*Circling widely, and gracefully rocking to and fro, the seed sinks slowly, almost unwillingly, to the earth. It needs only a breath of wind to make it rival the butterflies in flight*." The Zanonia seed can perform amazingly long glides, during which it demonstrates basic inherent stability. Flights of up to 6 km from the vine have been recorded.

The aerodynamic features of the Zanonia macrocarpa seed include[17]:

- Swept wing and forward CG for longitudinal stability (reduce pitch-up tendency)
- Swept wing and reflexed trailing edge to avoid pitch-up
- Reflexed trailing edge to provide quicker stall recovery
- Drooped leading edge for higher CLmax
- Dihedral for roll and yaw stability
- Large aspect ratio = 3 ~ 4 with a lift/drag ratio of 3 to 4
- Optimum center of gravity location for lowest rate of descent or highest duration of flight

A number of the early experimenters with tailless aircraft were inspired by the Zanonia's flying qualities. Igo Etrich adapted the principles he gleaned from his observation of the Zanonia seed to the design of his Leaf design in 1906. Rumpler developed his famous "dove utilizing a planform based on the Zanonia to which he added the "*tail of a dove*".

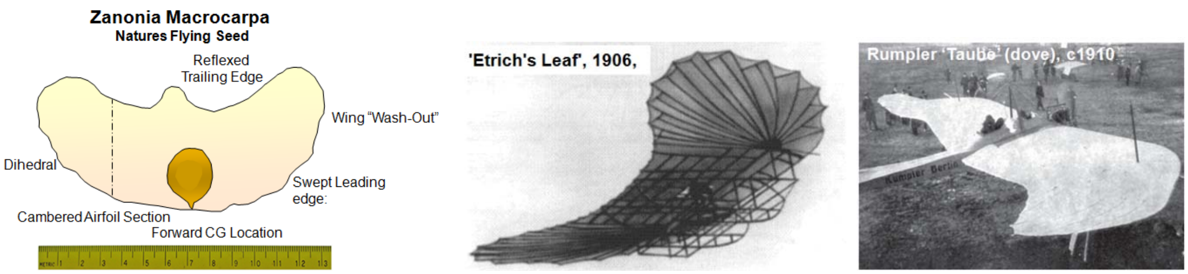


Figure 32: Early Innovation From a Seed

DiVinci utilized the concept of the spinning seed, shown in figure 33 to formulate his idea of the "air screw" which is considered to be the forefather of the autogyro, the helicopter as well as the propeller. Naturalist Christian de Launoy and his mechanic Bienvenu, about whom very little is known, developed a coaxial model of a simple helicopter powered by the tension in a bow. "*When the bow has been bent by winding the cord, and the axle placed in the desired direction of height -- say vertically, for instance -- the machine is released,"* the pair told the French Academy of Sciences in 1784. "*The unbending bow rotates rapidly, the upper wings one way and the lower wings the other way, these wings being arranged so that the horizontal percussions of the air neutralize each other, and the vertical percussions combine to raise the machine. It therefore rises and falls back afterward from its own weight."* This concept was also the first counter-rotating propeller design.

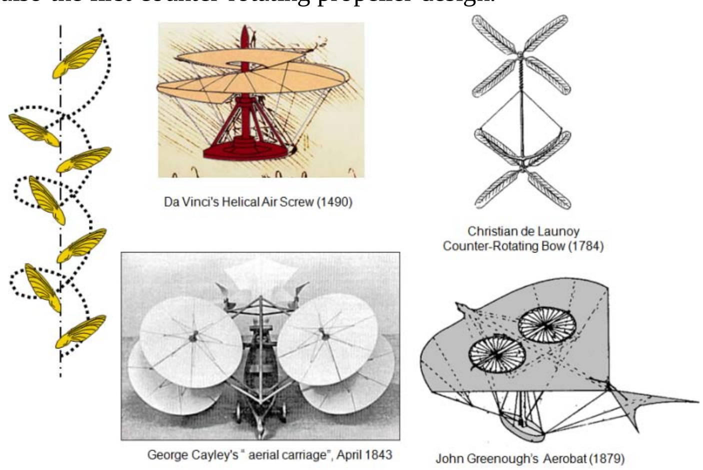


Fig. 33. Spinning Seeds , Air Screws and Helicopters

Large number of plants such as the dandelion use nature's version of the parachute to disperse their seeds as shown in figure 34. The very light seeds of the plant are attached to relatively large fluffy plumes that are released from the plant with a slight breeze. The high drag of the fluffy plumes results in very low sinking rates allowing the seeds to be blown and dispersed far from the plant[17].

The first known written account of a parachute concept is contained in daVinci's notebooks (cl495). The parachute concept that he conceived consisted of a cloth material pulled tightly over a rigid pyramidal structure. DaVinci never made nor tested his device. The first recorded successful test of such a parachute was made in 1595 in Venice by the inventor Fausto Veranzio who had examined DaVinci's rough sketches of a parachute, and Fausto set out to implement a parachute of his own. Twenty years later, he implemented his design and tested the parachute by jumping from a tower in Venice.

In World War I and World War II the classic parachute was widely used. During the early space projects[18], Rogallo developed a single membrane flexible wing, known as the parawing. Large parawings were designed for recovery of reentry vehicles. The parawing parachute was designed for maximum lift as opposed to the maximum drag of conventional parachutes.

The parafoil was invented in the middle 1960's by Domina Jalbert, a kite maker. The parafoil or ram-air parachute is a deformable airfoil that maintains its profile by trapping air between two rectangular shaped membranes, sewn together at the trailing edge and sides, but open at the leading edge. Several ribs are sewn to the inside of the upper and lower surfaces, maintaining an airfoil cross section in the spanwise direction.

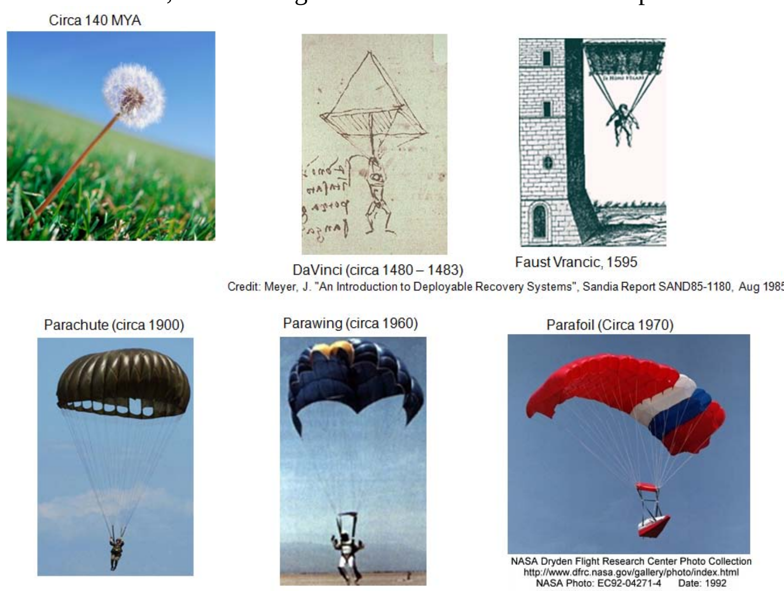


Figure 34: Drifting Seeds and Parachutes

X. KNOWLEDGE, TECHNOLOGY AND TOOLS FOR THE WRIGHT FLYER

When the Wright Brothers set as a goal, the development of the first powered aircraft they initiated their process by a search for all available knowledge of prior attempts to fly. Wilbur wrote a letter to the Smithsonian Institution requesting information and publications about aeronautics. Drawing on the work of Sir George Cayley, Chanute, Lilienthal, Leonardo da Vinci, and Langley, they began their flight experiments that year. They also built a strong networking relationship with Chanute who "*believing that the surest method is first to study past failures ---- made an investigation of the records of all the experiments,, which had been tried during the last two or three hundred years, in the endeavor to imitate the birds. This resulted in a number of technical articles which swelled into a book, in which the attempt was made to eliminate the causes of each failure; for up to that time there had been nothing but failures*".

Mr. Chanute in 1897 had published[14, 15] what may be considered to have been the state of the art understanding of ten critical elements that he considered to be essential to achieve successful powered flight. The first six, Chanute stated that they are well in hand and understood.

1. *THE SUPPORTING POWER AND RESISTANCE OF AIR* (Ability to Predict Lift and Drag)
    - *We are now enabled to calculate with some confidence the support (lift) which may be obtained by gliding at any given speed upon the air, and the power required to overcome the resistance (ie drag).* (Based on empirical formulae of Duchemin and Langley's experiments)
    - *More encouraging (lift) coefficients for concave surfaces have been obtained by Lilienthal in his experiments*.
2. *THE MOTOR, ITS CHARACTER AND ITS ENERGY.*
    - *For the first time the realization of a sufficiently light motor for a dynamic flying machine seems to be within sight.*
    - *It now seems probable that this will be accomplished with a petroleum engine.*
3. *THE INSTRUMENT FOR OBTAINING PROPULSION.*
    - *All sorts of contrivances have been proposed; reaction jets of steam or of compressed air, the explosion of gunpowder or even nitro-glycerine, feathering paddle wheels of varied design, oscillating fins acting like the tails of fishes, flapping elastic wings like the pinions of birds, and the rotating screw.*
    - *Mr. Maxim and Professor Langley have made many experiments to determine the best form, speed and pitch of the screw (propeller)to obtain thrust from the air, and have materially improved that instrument,*
    - *The Screw (propeller) seems likely to be the best device.*
4. *THE FORM AND KIND OF THE APPARATUS.*
    - *Almost numberless projects have been advanced, but they can all be classified under three heads.*
        - *Wings to sustain and propel. (Ornithopters)*
        - *Rotating screws to lift and propel, (Helicopters)*
        - *aeroplanes, to consist of fixed surfaces driven by some kind of propelling instrument.*
    - *The first two have been the first to be proposed and experimented with. They have many warm advocates at the present time,*
    - *Practical experiments made within the last five years seem to indicate that success will first be achieved with aeroplanes,*
5. *THE EXTENT OF THE SUSTAINING SURFACES.* (ie. what is the required wing area?)
    - *The problem, relating to the extent of surface required to support the weight of a man, has caused in the past active controversy and gathering of data.*
    - *It was perceived that in consequence of the law inherent to solids, the surfaces will increase as the squares, and the weights as the cubes of the homologous dimensions; it might well be that the additional relative weight due to the greater leverage should make it impossible to compass any larger flying machine than existing birds.*
    - *The experiments of Lilienthal, demonstrated that a man's weight can be well sustained, at 22 to 25 miles an hour, by an apparatus with an area /weight ratio ~ 1.25*
    - *This apparatus need not weigh more than from 23 to 36 pounds, without motor or propeller, so that if the latter weigh some 60 pounds more, --- carrying a man of about 150 pounds, upon sustaining surfaces of approximately 200 square feet in area*. (W/S ~ 1.25)
6. *THE MATERIAL AND TEXTURE OF THE APPARATUS.*
    - *The sixth question relates to the material to be selected for the framing of the machine, for the motor, and to the texture of the sustaining surfaces. Nature accomplishes her purposes with bone, flesh and feathers, but man has at his command metals, fuel and textile fabrics*
    - *For a beginning wooden frames covered with textile fabrics will answer for a beginning.*
7. *THE MAINTENANCE OF THE EQUILIBRIUM.*
    - *The seventh problem relates to the stability of the apparatus in the air, and especially in a wind.*
    - *This equilibrium must be maintained at all angles of incidence and under all conditions of flight.*
    - *Until automatic equilibrium is secured, and safety is ensured thereby, under all circumstances, it will be exceedingly dangerous to proceed to apply a motor and a propeller.*
    - *Man will have to work out this problem thoroughly, if he is ever to make his way safely upon the air.*
8. *THE GUIDANCE IN ANY DESIRED DIRECTION.* (Control Capability)

- *The eighth problem relates to the steering. It has been generally supposed that this would be best effected by horizontal and vertical rudders,*
- *The experiments of Lilienthal, have shown that slight changes in the position of the center of gravity are immediate and effective.*
- *It might be preferable to provide moving mechanism within the apparatus itself, to shift the surfaces so as to bring back the varying center of pressure over a fixed center of gravity, and that in such care the operator need not move at all, except for the purpose of steering.*
- *Two forms of apparatus have been evolved, each equipped with a different device, which are now believed to be materially safer than any heretofore produced.*
- *This problem cannot be said to be fully worked out, but it is not that a good deal of experimenting will be required, and that such experiments will be fraught with danger.*

9. *THE STARTING UP UNDER ALL CONDITIONS.* (Takeoff capability)
   - *A really adequate practical flying machine will have to possess the power of starting into the air under all conditions*
   - *Three principal methods have been experimented with:*
     - *By acquiring speed and momentum using such appliances as railway tracks*
     - *Utilizing the force of the wing.*
     - *By the reaction of rotating screws --- this will eventually supersede the two others.*
   - *This problem is as yet unsolved.*
10. *THE ALIGHTING SAFELY ANYWHERE.* (Landing Capability)
    - *Alighting safely anywhere is of vital consequence and is also an unsolved problem.*
    - *The best method proposed involves the selection of a smooth soft piece of ground and the alighting thereon at an acute angle. (Smooth runway)*
    - *It would be preferable ---- to imitate the maneuver of the bird who stops his headway by opening his wings wide , tilting back his body back and obtaining the utmost --- retardation from the air before alighting upon the ground.*
    - *It would be preferable to utilize the reaction of a rotating screw to diminish the forward motion.* [It is interesting to note that the recommendations proposed by Chanute are quite similar to present day landing configurations and procedures including high lift systems with extended leading and trailing edge flaps, spoilers and reverse thrust]

Chanute went on to say "*These last two problems – the rising and alighting safely, without special preparation of the ground – seem very difficult and are probably the last of which will be worked out.*"

The general common "Expert" belief at the time when the Wright brothers started the pursuit of their dream was that powered manned flight was not possible. This is evident by the quotes below of key scientific experts of the day.

Distinguished scientist (1895): ----- "*artificial flying machine is impossible for three reasons:*

1. *Nature, with her utmost effort, had failed to produce a flying animal of more than fifty pounds in weight.*
2. *That the animal machine was far more effective than any that man may hope to make.*
3. *That the weight of any artificial flying machine could not be less, including fuel and engineer, than 300 or 400 pounds.*"

Lord Kelvin, Royal Society President ----- 1895 "*Heavier-Than-Air Flying Machines are Impossible*"

Simon Newcomb (1835-1909), astronomer, head of the U. S. Naval Observatory. ----- " *no possible combination of known substances, known forms of machinery, and known forms of force, can be united in a practical machine by which man shall fly long distances through the air...*"

Widely attributed to George W. Melville, chief engineer of the U.S. Navy, 1900 ----- "*If God had intended that man should fly, he would have given him wings*."

Simon Newcomb, Canadian-born American astronomer, 1902 -----"*Flight by machines heavier than air is unpractical and insignificant, if not utterly impossible.*"

Even Wilbur Wright had his moments of doubt: ……. in 1901 *"I said to my brother Orville that man would not fly for fifty years. Two years later we ourselves made flights"*.

This was the "current" technical knowledge base and expert advice that formed the understanding of the impossibility of powered. In spite of this prevailing negative mental environment, the Wright brothers believed so strongly in their dream that in a short period of three years they achieved it.

Their accomplishment provides a vivid example of two powerful concepts:

1. *"Believe you can, or believe you can't, either way you will be right"*
2. *"If the dream is big enough the facts don't count"*

The Wright Brothers launched their systematic experimental studies and technology developments following the ten critical issues and design guidelines defined by Chanute.

Although the obvious focus of the Wright brothers technology development efforts were focused on solving critical elements 7 and 8 (stability and control), there were many unresolved issues associated with elements 1 through 6. The development timeline of the Wright Brothers success is summarized in figure 35.

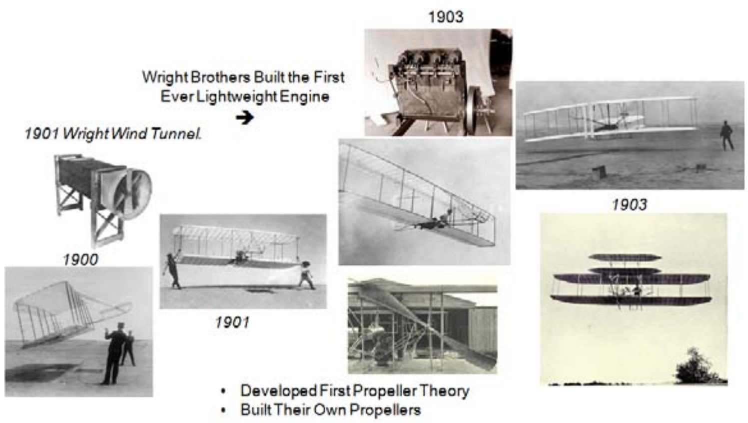


Figure 35: Wright Brothers Aircraft Development

In 1900, 1901, and 1902, Wilbur and Orville Wright, achieved a considerable advance over all previous flying results. They were bold enough to be the first to place a man prone upon a gliding machine, instead of upright (for safety in alighting), and they used wing surfaces twice the area which previous experimenters had found it practicable to handle in the wind.

Following their first glider in 1900, they discarded the tail, and substituted for it a hinged horizontal canard at the front, which could easily be operated by the pilot while under way. Their theory was that the pilot should constantly balance and guide the machine by the action of the canard, steering to the right or left by warping one wing or the other using light control strings leading to his hands.

The control of the machine by the canard in front was found to be even better than had been hoped, and the landings were safely made at speeds of 10.m. per second. The experiments of 1902 marked another great advance and mark a decided advance in the techniques of flight.

The apparatus could now be controlled so well that Wright brothers deemed it safe to pass on to the construction of a full flying machine equipped with a motor and propeller. They faced another seemingly daunting obstacle; the necessary lightweight engine did not exist. Consequently they designed and built the first lightweight aluminum engine. They also designed and built their own propeller. In the process they developed the first propeller theory. S in 1903, and on the 17th of December of that year, after many trials and modifications, they had the satisfaction of making four dynamic flights from level ground against a wind of 10 m. per second-the first flight being of about 12 seconds, and the last of 59 seconds, when 260 m. were covered at a height of about 2 m. from the ground.

Various sub-systems that made up the systems of systems design of the Wright Flyer are shown in Figure 36.

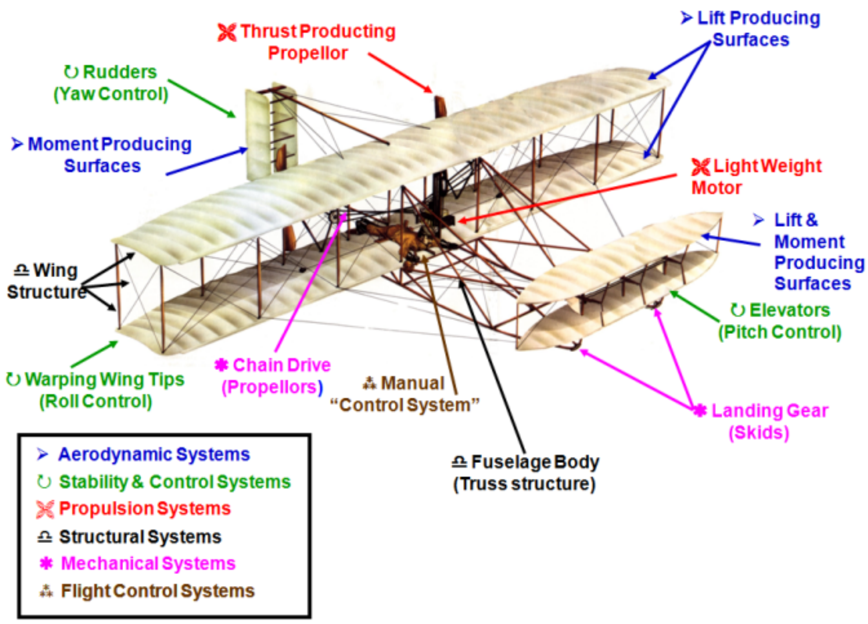


Fig. 36. Wright Brothers Flyer System of Systems

XI. MORE EXPANDED VIEW OF THE EVOLUTION OF FLIGHT

The importance of developing and using the complete set of engineering tools will be briefly discussed with focus on the aerodynamic tool set shown in figure 37.

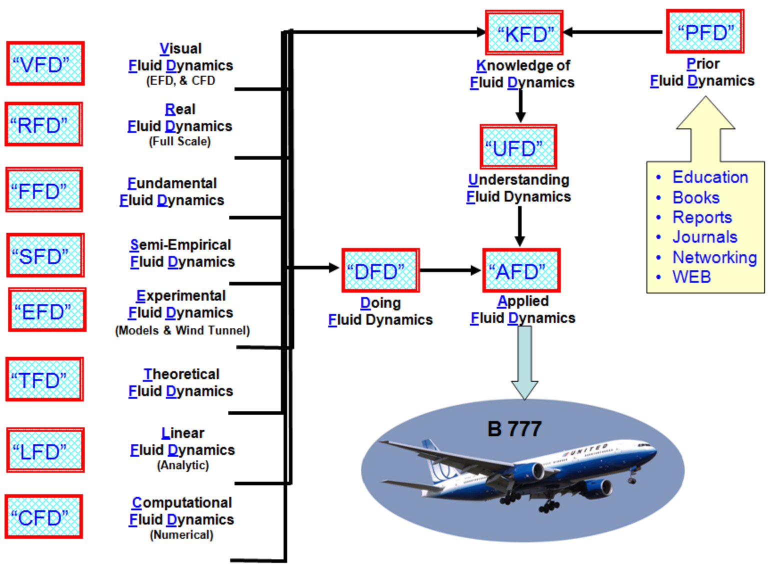


Fig. 37: Aerodynamic Tool Set

The development of our flying vehicles dreams, visions, attempts and ultimate achievement were enabled by the progressive synergistic developments in aerodynamic concepts and tools and other critical technologies developments as shown in Figure 38.

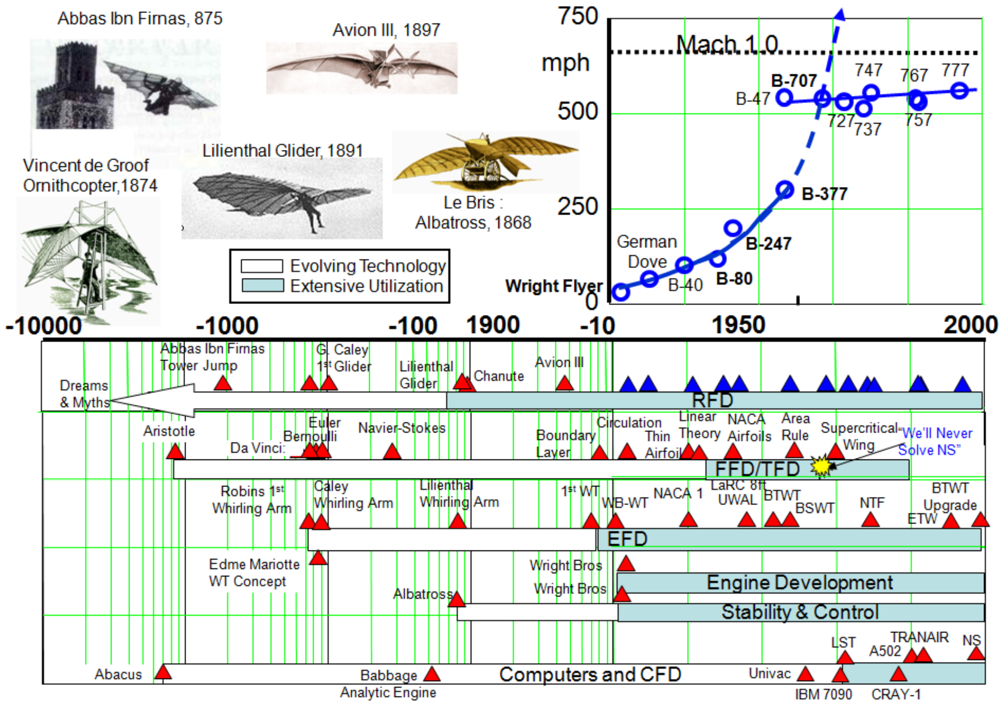


Figure 38: History of Commercial Air Travel

The evolutionary events leading to manned flight occurred over thousands of years. For as long as man has harbored the desire to fly, many attempts were made to emulate the flight of birds initially by strapping on some apparatus that had some resemblance to a bird and then leaping off a tower or other high prominent location. This type of event was repeated over and over, but seldom ever more than once by the same person. These Real Fluid Dynamics, RFD, experiments, which we will define as manned flight experiments, have occurred over thousands of years. Most of these early experiments failed, many of which suffered serious consequences. Lilienthal's and Chanute's numerous glider experiments represent the first extensive exploratory studies of manned flight.

The Fundamentals of Fluid/Flight Dynamics, FFD, equations were developed over a period of approximately a thousand years before the Wright Brothers. These include all the contributions by daVinci, Euler, Bernoulli, Navier-Stokes as well as boundary layer theory, the concept of circulation and linear theory formulations. However the ability to utilize these formulations awaited the development of the digital computer and consequently, had rather little significance in enabling early powered flight.

Computational Fluid Dynamics, CFD, did not come into existence until about 1960. The impact of CFD, since that time, has become incredibly significant.

The earliest form of Experimental Fluid Dynamics, EFD, activities utilized whirling arm mechanisms. These did provide some basic understanding of lift and drag forces. The concept of the wind tunnel was conceived about 200 years before the Wright Brothers. The first tunnel was actually built a few years before 1900. The Wright Brothers built one of the first wind tunnels. Their experiments provided valuable information and data that were used to support their flight experiments and ultimately was a critical element in their success.

Two of the supporting critical enabling technologies included a fundamental understanding of Stability & Control Flight Dynamics and the development and flight validation of simple but effective control mechanisms. In addition, the Wright brothers built the first light weight aluminum engine which they used for the Wright Flyer of 1903.

This development process leading to the first manned flight clearly illustrates a typical feature of the development of new technologies and concepts. This is the requirement to advance on many disciplinary or technical fronts.

Following the pioneering developments of the Wright Brothers, the demand soon arose for greater flight capabilities. The further development of the aerodynamic tools, together with the developments in other technologies, lead to dramatic increases in the performance and operational characteristics of aircraft.

The two most critical tools of the aerodynamicist, (KFD and UFD), are intimately related but fundamentally different. Knowledge of Fluid/Flight Dynamics is similar to a collection of pieces and perhaps partly assembled pieces of a great puzzle. The collection generally may be lacking some of the key pieces. In addition some of the pieces may be invalid or from a different puzzle. Our understanding, UFD, is the image that we create by assembling the pieces we have accumulated as well as inferring the nature of the missing pieces. Man's knowledge and understanding of the nature, of biomechanics of flight has evolved through the systematic development and utilization of the engineering tools and processes, as well as critical synergistic and enabling developments in many other technical disciplines. The expanded use of our tools have provided many additional pieces to our knowledge and understanding puzzle that are reflected in the increased capabilities and sophistication of our modern flight vehicles.

XII. CO-EVOLUTIONARY DEVELOPMENTS OF TECHNICAL FLIGHT

The development or "evolution" of aircraft technology has many apparent parallels with the evolutionary processes of nature even though as previously discussed evolution, and the development of technology are fundamental different.

Coevolution is a major driving force for technology developments especially if we consider in addition to the aircraft manufacturers, such elements as the propulsion manufacturers, the competition, the users, the operational facilities and environments.

- "Competition" between different manufactures to produce the "best" overall aircraft favored by the customers and users.
- Predator vs prey for military defensive and offensive developments, and for detection and evasion developments.
- "Mutualism" between aircraft operations and airports
- Mutualistic developments between airframe manufactures relative to safety, security, environmental concerns and airspace management.
- Special interiors for airlines are an example of a commensalism symbiotic coevolutionary relationship between the manufacturer and the airlines.

The evolution of technology is somewhat related to the Lamarckian theory of evolution which assumed that new traits were acquired by need and usage and these new traits are passed on to subsequent generations as long as they were used. New technology developments are driven by need and these developments will indeed be passed on to subsequent generations as long as the technology is used.

An example of mutualistic coevolutionary developments between aircraft, airports and resorts are shown in figure 39. The demand for increased commercial air flights have led to developments in airports. The developments in the airports have consequently increased utilization by commercial airplanes. The increasing number of airport related operating restrictions have led to technology improvements in the airplanes.

Similarly improvements in resorts entice people to desire to travel to them. The resulting increased demand for air travel has led to more and improved airplanes

Fig. 39: Commercial Aircraft Mutualistic Relations

The competition between competing aircraft has been a strong evolutionary driving force in the technical growth of both commercial and military aircraft. The competition includes both intraspecific competition between like species of aircraft and interspecific competition between different species of aircraft.

Figure 40 shows an example of commercial aircraft intraspecific competition.

Fig: 40: Commercial Aircraft Intraspecific Competition Developments

Boeing introduced the B-247 all metal advanced commercial aircraft in 1933. This was a major technology development including an all-metal semi-monocoque fully cantilevered wing, wing flaps, retractable landing gear, control-surface trim tabs, and an autopilot. The b-247 was faster than the U.S. premier fighter aircraft. The payload was less than 14 passengers. 75 B-247s were built.

Douglas aircraft responded in 1934 with the DC-2 with similar technical advancements to the B-247, however the DC-2 could carry 14 passengers and thus captured the market from the B-247. 156 DC-2s were built.

Douglas then introduced the DC-3 in 1935.The speed and range of the DC-3 revolutionized air transport in the 1930s and 1940s. The airplane carried 28 passengers and had a lasting impact on the airline industry and World War II. It is considered to be one of the most significant transport aircraft ever made. 10,928 DC-3s were built (many for the military.

It is seen that the previously discussed competitive exclusion principle is a success and survival factor for aircraft as well as for nature. *No two species of similar requirements can long occupy the same niche (coexist).*

Figure 41 contains examples of both intraspecific and interspecific competition for commercial aircraft.

The Douglas DC-7 was a transport aircraft built by the Douglas Aircraft Company from 1953 to 1958. It was the last major piston engine powered transport made by Douglas, coming just a few years before the advent of jet aircraft. 348 were produced.

In order to once again be the leading competitor in the commercial aircraft business, Boeing took the bold step of starting to plan a pure-jet airliner as early as 1949. Boeing's military arm had gained extensive experience with large, long-range jets through the B-47 Stratojet (first flight 1947) and the B-52 Stratofortress (1952). Boeing ushered in the jet age with the introduction of the B-707 in 1957. Boeing delivered a total of 1,032 Boeing 707s, which dominated passenger air transport in the 1960s and remained common through the 1970s. The B-707 established Boeing as one of the largest makers of passenger aircraft.

This is an example of interspecific competition between propeller driven, unswept wing aircraft and jet powered swept wing aircraft.

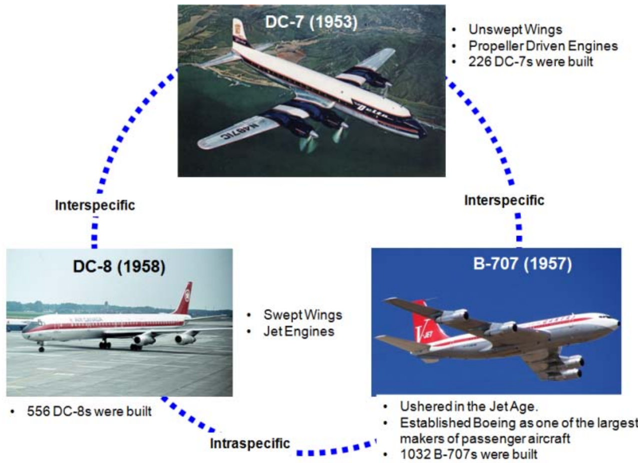


Fig. 41. Commercial Aircraft Competition Co-Evolution

As an example of intraspecific competition, Douglas responded to the B-707 competition with the introduction of their own swept wing jet aircraft the DC-8 which captured some of the market from Boeing by delivering 556 aircraft.

Figure 42 shows an example of competition between military aircraft. The competition to build the US Joint Strike Fighter was between the Boeing X-32B Demonstrator and the Lockheed Martin X-35A Demonstrator. The Lockheed Martin Configuration was declared the winner and consequently the winners were awarded the contract to build the F-35 Joint Strike Fighter.

Fig. 42: Joint Strike Fighter Competition

Figure 43 shows and example of predator / prey mutualistic between the military aircraft of the Allies and those of their enemies.

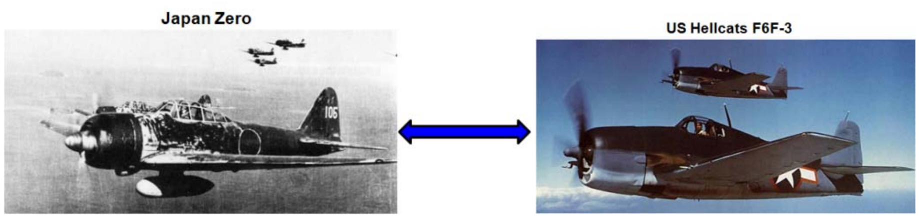


Fig. 43: World War 2 Fighter Aircraft Competition Co-Evolutionary Developments For Superiority in the Pacific

XIII. AIRCRAFT EVOLUTIONARY DEVELOPMENTS AND TECHNOLOGY NEEDS

Figure 44 illustrates the paradigm shift in commercial aircraft design drivers from the earliest aircraft to the commercial aircraft of today[19].

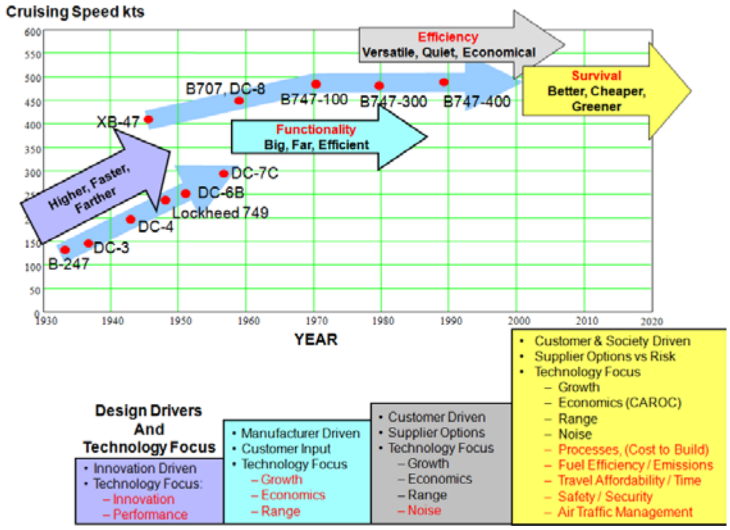


Fig. 44. Commercial Aircraft Design Drivers and Technology Focus

The designs of early propeller commercial aircraft were innovation driven with the primary goal of increasing aircraft performance. That is to fly *higher, faster and farther* as well as to become bigger.

The introduction of jet powered swept wing aircraft provided revolutionary increases in aircraft size, cruise speed, cruise altitude and range. The cruise speeds and altitudes have remained essentially constant for subsonic aircraft jet aircraft. The early jet aircraft designs were determined by the aircraft manufacturer with inputs from the airline customers. Technology advancements were focused on increased *functionality* including aircraft growth capabilities, operating economics and range.

The designs of the third generation of commercial aircraft were increasingly driven by customer inputs with supplier options and the areas of technology development were focused on various *efficiencies* including family growth concepts, improved economics, increased range and aircraft noise reduction.

The new generations of commercial aircraft designs will be both customer and society driven. The manufacturer will provide design options determined by strategic assessments of economic risks and opportunities. The technology focus areas will include in addition to those of previous aircraft, more efficient manufacturing processes, fuel efficiency and reduced emissions, travel time and affordability, safety and security, and improvements in the ATM system. Because of the highly competitive nature of today's market place, one of the primary goals of new aircraft is that of basic company *survival*. Unless a new airplane is the best offering to the airlines, lack of sales could force a company out of business.

If we compare the technology drivers of nature (figure 12) with the technology drivers for commercial aircraft (figure 44) we arrive at the observation shown in figure 45. The evolutionary driver for nature's flyers was initially survival, and then gradually progressed through stages of efficiency, functionally and ultimately higher, faster and farther. The technical driver for manned commercial flight, however, appears to have progressed in the opposite order. I am not sure if this is biologically accurate, but it is an interesting observation.

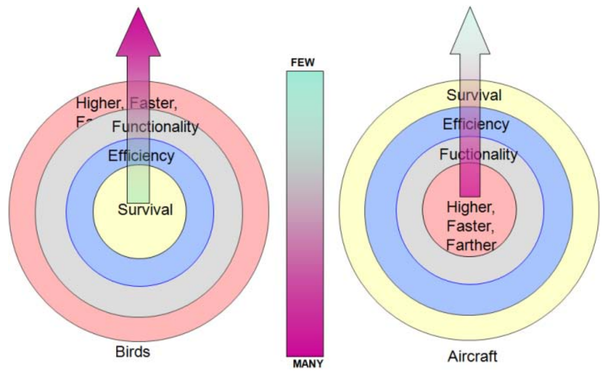


Fig. 45. Why Did Flight Evolve? --- Contrasting Technology Development Drivers

XIV. OPPORTUNITIES AND NEEDS FOR INNOVATION

"The Rapid Journey From the First Tentative Flights to the Modern Airliner is a Testament to the restless search for technological improvement that has long characterized the aircraft business.[20]". This rapid journey is evident in dramatic change in aircraft configurations as shown in figure 46. Forty six years after the feeble but historically significant flight of the Wright Brothers, the sleek, swept wing jet powered B47 flew. Forty six years later the B777 made its debut in the commercial transport arena.

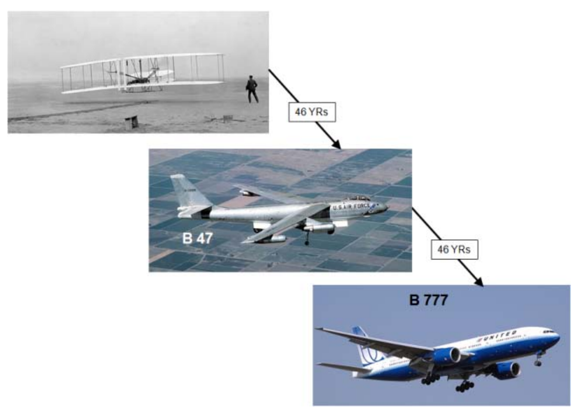


Fig. 46 The Rapid Technical Growth of Aircraft

"A generation ago, "Higher, Further, Faster" were the imperatives for any vision of the future for air transport. Now they are "More Affordable, Safer, Cleaner and Quieter", -- The key to securing these objectives is investment in Research and Technology" The high degree of design sophistication of the modern aircraft can be seen by the areas defined by CFD and multi-disciplinary design and optimization techniques [22] in the B787 as shown in figure 47, and by the advanced design and operating features of modern military aircraft as shown in Figure 48.

Fig. 47. CFD contributions to the 787

Fig. 48. Aircraft Multi-Mission Advanced Technology Concepts

Aerodynamics together with structural and manufacturing considerations largely define an airplanes exterior contours. The technological progress in aeronautics is often associated with size and shape of the aircraft. It can be argued with some degree of validity, that the vast majority of existing aircraft were established approximately 65 to 70 years ago[23]. Ingo Rechenberg[24] said that he finds it "*very remarkable that after 100 years development a modern aircraft still looks like a bird: a spindle body, the wing in front and the elevator behind. That's the solution of biological evolution and that's still the basic concept of a modern aircraft*." However this certainly does not mean that man has exhausted all possible aircraft related innovative or creative technology developments.

The needs for continued technical innovation and development for aircraft far exceeds just the external shape or operating procedures.

The needs for technical innovation permeate every element of the systems of system. Some of the general critical areas for which technology developments are in need commercial air transportation include:

- Factors that affect the costs to build, own, operate and maintain a commercial aircraft
- Aircraft community noise reduction
- Design and Manufacturing Processes, (Cost to Build)
- Emissions / Fuel Efficiency
- Travel Affordability / Time / Comfort
- Safety / Security
- Air Traffic Management

XV. CONCLUSIONS

Where do we go from here in the next 100 (or even 20) years? There are at least three possible answers, as shown in figure 49 all of which are likely one way or another:

- Keep running harder and harder (i.e. doing what we have been doing) to develop innovation solutions for today's classes of aircraft.
- Schedule a breakthrough (e.g. a possible Sonic Cruiser II via large reductions in sonic boom intensity and "aerospace plane" technology) or an invention (e.g. economically and logistically viable alternatives to fossil fuel propulsion schemes for transport aircraft).
- Start a whole new game - one in which the gap between the possible and the achieved is once again very large, e.g. the whole range of possibilities for uninhabited [combat] air vehicles (UAV/UCAV) type vehicles, which represent a complete fusion of traditional and emergent aerospace vehicle technology with "information and communications technology."

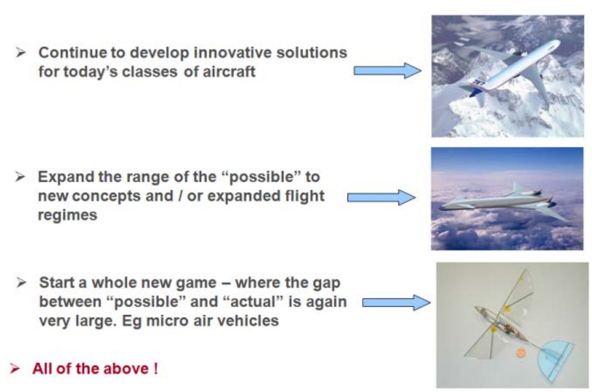


Fig.49. Aircraft Future Technology Needs and Opportunities

A general characteristic of technology development is the need to advance the technology on all fronts. Consequently each and every component technology or systems development becomes a critical element in the overall innovative development processes. With our view of an aircraft as an integrated system of systems, this implies that a technology development in one system no matter how seemingly small or unrelated can become an important element in the overall system development. Consequently one should be open beyond their immediate technical discipline to any concept that offers potential improvements for the system as a whole.

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