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The Retractable Airplane Landing Gear and the Northrop "Anomaly": Variation-Selection and the Shaping of Technology

WALTER G. VINCENTI

Airplane designers today routinely provide their high-performance aircraft with a landing (and takeoff) gear that retracts inside the vehicle in flight. Few people apart from the designers give attention to that fact. As with other devices that attract little notice, however, the retractable landing gear has a history of more than incidental interest. Looked at deliberately, its story contains lessons about the processes of learning and change in engineering.

This article does not pretend to a full history of the retractable gear. Such a task would call for a book.[1] Though I aim to put the story in context, I shall focus primarily on an episode in the United States in the first half of the 1930s, when the retractable gear was entering prominently and permanently into airplane design. In that period, as retractable gear were appearing on a series of innovative airplanes, a succession of high-performance craft from the noted designer John Northrop continued to exhibit a streamlined fixed undercarriage. These beautifully trim aircraft are certain to be remembered by any observer of the aeronautical scene at the time—as was I as an aviation enthusiast in high school. Thinking back on them prompted me to wonder: How was it that Northrop, who led the way in other respects, was apparently so slow to adopt retraction? An answer to this

MR. VINCENTI is a member of the Department of Aeronautics and Astronautics at Stanford University. He thanks the host of people who helped collect and comprehend the material in this article: Richard Allen, Gerald Balzer, Glenn Bugos, Ira Chart, Edward Constant, Fred Culick, David Edge, the late Edward Heinemann, Nicholas Hoff, Thomas Hughes, John Kimball, Stephen Kline, Ilan Kroo, Gerald Landry, Edwin Layton, Mark Levinson, Robert McGinn, Anne Millbrooke, Russell Robinson, Eric Schatzberg, Paul Seaver, Richard Shevell, Richard Smith, and a *Technology and Culture* referee.

[1] For a brief outline of the history of the airplane landing gear, both fixed and retractable, see C. Ellam, "Developments in Aircraft Landing Gear, 1900–1939," *Transactions of the Newcomen Society* 55 (1983–84): 48–51.

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question, I hoped, might supply evidence concerning the variation-selection model for the growth of engineering knowledge put forward in my recent book.[2] The story turned out more instructive than I anticipated. Beyond its significance for the variation-selection model, it has implications—cautionary, I believe—for the social study of technology. I will take up these matters following a narrative of the Northrop episode and its context.

The Usual View

Adoption of retractable gear contributed to what John Rae calls the "airframe revolution" of the early 1930s. As discussed in the volumes by Rae and by Ronald Miller and David Sawers, American designers combined this and other innovations—aluminum stressed-skin structure, wing flaps, and the controllable-pitch propeller—into what would remain the dominant configuration for both military and civil purposes for the next twenty years. This synthesis is seen as coming about through a series of ten or so key land-based aircraft, beginning with the Boeing Monomail and Northrop Alpha, single-engine commercial designs of 1930, and culminating in the well-known Douglas twin-engine airliners, the DC-1, -2, and -3 of 1933–36. The various innovations, introduced in different combinations as the series grew, came together as a whole in the DC-1. Of the series, the Monomail (fig. 1) and the Lockheed Orion, an advanced but still wood-structured transport of 1931 (fig. 2), are often pointed to as pioneering use of retractable gear. Since this airframe revolution, the retractable undercarriage has been an accepted and essential element of high-performance land-based aircraft.[3]

To the extent they have examined the issue, historians tend to see the introduction of the retractable gear as an essentially reasoned and ordered affair. Lawrence Loftin, in his detailed and technically informed book *Quest for Performance,* compares the numerical drag coefficient of the Orion with that of Lockheed's earlier fixed-gear Vega and states that, generally speaking, "the spectacular reductions in drag associated with . . . use [of retractable gear] on an

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[2] W. G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore, 1990), chap. 8.

[3] J. B. Rae, *Climb to Greatness: The American Aircraft Industry, 1920–1960* (Cambridge, Mass., 1968), chap. 4; R. Miller and D. Sawers, *The Technical Development of Modern Aviation* (New York, 1970), pp. 18–20, 47–50, 63–65, 73–75, 84; P. W. Brooks, *The Modern Airliner: Its Origins and Development* (London, 1961), chaps. 1, 3. Other craft commonly mentioned in the series are the following, all with twin engines and retractable gear: Boeing B-9 and Martin B-10 bombers (1931–32), Boeing 247 transport (1933), and Lockheed Electra transport (1934).

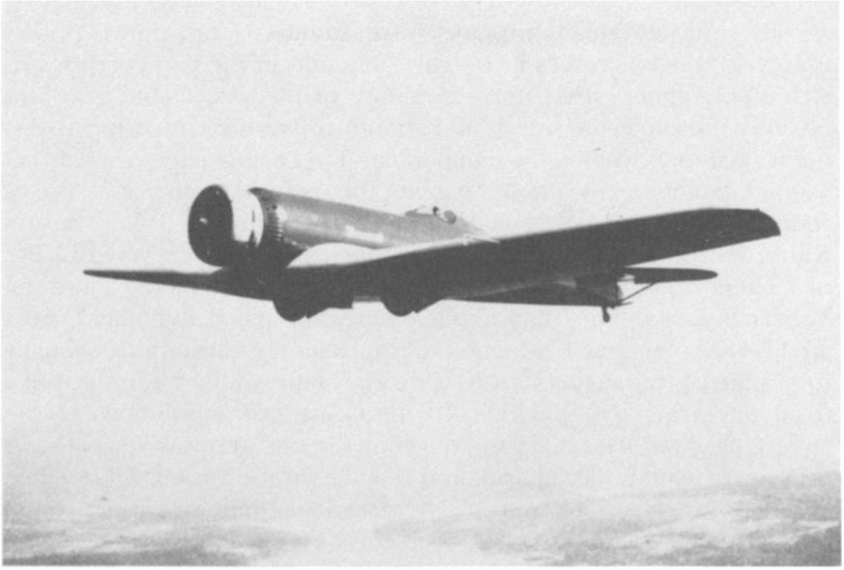

FIG. 1.—Boeing Monomail. (Courtesy of the Boeing Company and Paul G. Spitzer.)

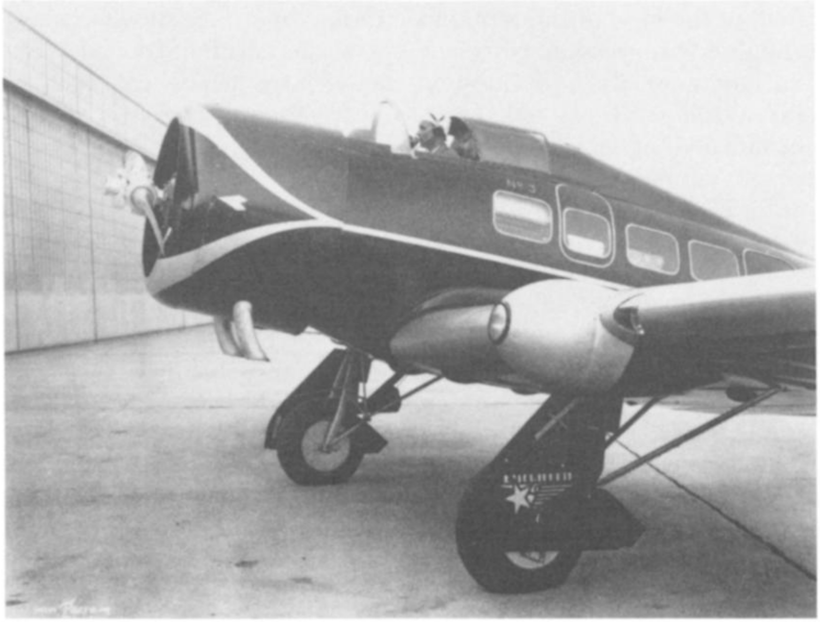

FIG. 2.—Lockheed Orion. (Courtesy of Richard S. Allen.)

aerodynamically clean airplane were found to far outweigh the relatively small increases in weight." Though in the end correct, this statement suggests that the desirability of the retractable gear was obvious and subject to simple and straightforward engineering assessment. Walter Boyne, in his semipopular *The Leading Edge,* casts his net wider, mentioning, in various contexts, the sporadic, anticipatory use of retractable gear on an assortment of early airplanes: J. W. Martin's Kitten of 1917 (which was incapable of flight), the Dayton Wright RB-1 of 1920 (a remarkably advanced design generally for its day), and the Verville Sperry R-3 of 1922. Though increasing speed and other factors are likewise mentioned, adoption in the 1930s appears as an essentially foresighted progression, first to a variety of streamlined fairings for a fixed undercarriage, and then to the clearly "ideal solution" of the retractable gear. The main unknown in the last step was what sort of gearing, actuating mechanism, and the like, to use for retraction. The question was thus not whether a retractable landing gear ought to be used—that was self-evident; the problem for the engineer was how best to achieve this end structurally and mechanically. Views such as these, I submit, underlie the usual historical references to the retractable gear.[4]

The Northrop Anomaly

Within the view of the Monomail, Orion, and their successors as a foresighted progression, Northrop's persistence with fixed gear seems a curious anomaly. The question in the introduction can then be recast as follows: If retraction was so clearly the way to go, why did an innovative designer like Northrop continue on such a seemingly aberrant course?

John K. ("Jack") Northrop was, by anyone's count, one of the most creative and influential airplane designers in the quarter-century following the mid-1920s. After work as a self-taught draftsman-engineer with the Loughead brothers, Malcolm and Allan, in Santa Barbara and with Douglas Aircraft in Santa Monica, Northrop in 1927 joined Allan Loughead in the recently formed Lockheed Aircraft Company in Hollywood. At Lockheed he became well known as designer of the innovatively streamlined Vega, a cantilever high-wing wood-structured monoplane that blazed trails and set records at the hands of Hubert Wilkins, Amelia Earhart, Wiley Post, and others. Parting company with Lockheed in 1928, he became the guiding spirit of the Avion Corporation, where he built an experimental all-metal

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[4] L. K. Loftin, Jr., *Quest for Performance: The Evolution of Modern Aircraft* (Washington, D.C., 1985), p. 89; W. J. Boyne, *The Leading Edge* (New York, 1986), pp. 10, 77–78, 90–93, 189–90.

monoplane, described at the time as a "flying wing." Though the pilot and engine were indeed enclosed within the unusually thick wing, the craft had in fact a tail supported by twin booms.[5] At the beginning of 1930, Avion became a division of United Aircraft and Transport Corporation, an aviation holding company, and its name was changed to the Northrop Aircraft Corporation. This turned out to be the first of a succession of three companies to bear the Northrop name. With these companies, Northrop led the design of a number of notable airplanes. He is probably best remembered for his giant experimental (true-)flying-wing bomber of the late 1940s.[6]

The Northrop airplanes that concern us here, however, are the Greek-letter series coincident with—indeed, part of—the airframe revolution. The Northrop Alpha (fig. 3) inaugurated the series in March of 1930. Like the contemporary Boeing Monomail, the Alpha featured stressed-skin all-metal construction equal or superior to previous wooden structures in terms of strength in relation to weight. Where the Monomail's wing used more or less conventional (though aluminum) truss-type spars and ribs, however, the Alpha's wing was made up throughout from aluminum sheet, cut and formed into channel-shaped elements for the spanwise and chordwise components of the internal frame. These were then riveted to one another and to the wing skin to form, in effect, an assembly of contiguous, more or less rectangular, boxes. This relatively light, inexpensive, and rugged multicellular structure, which Northrop had employed also on the Avion "flying wing," was described by *Aviation* magazine as a "radical and promising innovation." Probably Northrop's most important contribution to aeronautics, it was imitated, with modifications, in the Douglas DC-series and later aircraft.[7]

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[5] J. K. Northrop, "The All-Wing Type Airplane," *Aviation* 28 (March 29, 1930): 645–48.

[6] For Northrop, the Avion Corporation, and the three Northrop companies till 1939, see R. S. Allen, *The Northrop Story, 1929–1939* (New York, 1990). Pages 133–46 contain a short history of every Northrop airplane produced in that period; much of the information on Northrop aircraft comes from this source. For mainly the third Northrop company, see F. Anderson, *Northrop: An Aeronautical History* (n.p., 1976). For Northrop airplanes, see also G. Balzer, "The Aircraft of Jack Northrop," *Journal of the American Aviation Historical Society* 26 (Spring 1981): 80–87. For the Vega and the Lockheed Company, see R. J. Francillon, *Lockheed Aircraft since 1913* (London, 1982); and R. S. Allen, *Revolution in the Sky: The Lockheeds of Aviation's Golden Age*, rev. ed. (New York, 1988).

[7] "The Northrop 'Alpha,'" *Aviation* 29 (December 1930): 361–62, quoted phrase on 361; K. D. Wilson, "Jack Northrop's Metal Miracle—the Alpha 4A," *Model Aviation* 6 (October 1980): 55–60, 122–24. For Northrop's multicellular wing structure, see also Miller and Sawers, pp. 64–65; N. J. Hoff, "A Short History of the Development of Airplane Structures," *American Scientist* 34 (July 1946): 370–88; Northrop, p. 646; Brooks, fig. on p. 81.

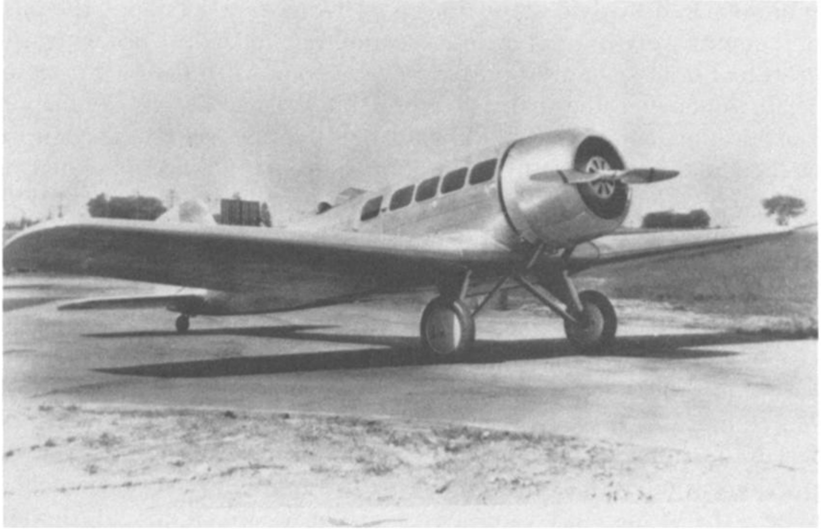

FIG. 3.—Northrop Alpha, original passenger version, with tripod landing gear. (Courtesy of John B. Kimball.)

The Alpha differed from other craft in the airframe revolution, however, by retaining a fixed landing gear. In its initial version, this gear had the unstreamlined tripod (or split-axle) arrangement common on other airplanes of the time (see fig. 3). Transcontinental and Western Air (TWA), forerunner of Trans World Airlines, acquired thirteen Alphas of this type. These it used successfully, beginning in 1931, to establish twenty-four-hour mail service between New York and Los Angeles.[8]

Jack Northrop, a self-described "nut about streamlining,"[9] was not unaware, of course, of the aerodynamic attractions of retractable gear. As part of a generalized discussion of prospective design refinements that introduced an article of early 1930 on his "flying wing," he stated that in general "Landing gear retraction offers one of the largest theoretically possible [aerodynamic] gains." He had in 1929, in fact, already used a retractable gear briefly on the "flying wing." This gear, designed by Northrop and built by the Menasco Manufacturing Company, proved troublesome in cross-wind takeoffs and landings in early flight tests; it was replaced with fixed gear to expedite the testing and never reinstalled before the "flying wing" was discontinued in favor of the increasingly important fixed-gear Alpha. Later in 1929,

[8] Allen, *Northrop,* p. 18.

[9] Quoted by Miller and Sawers (n. 3 above), p. 62.

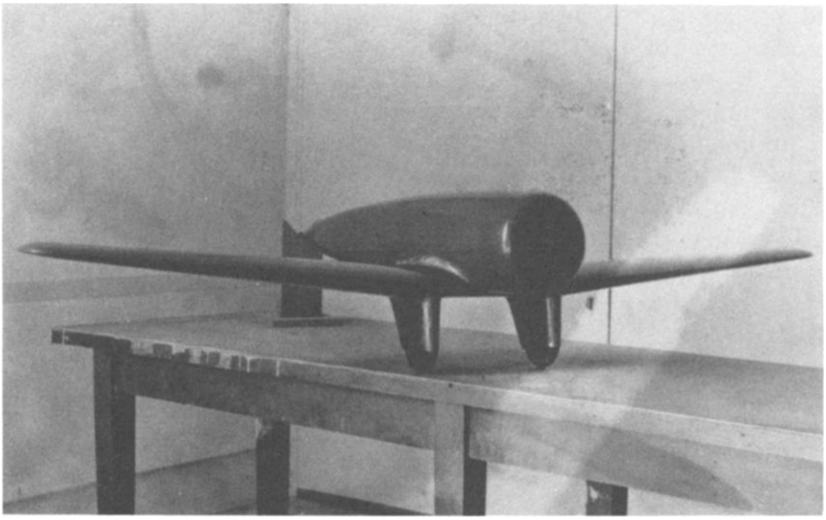

FIG. 4.—Wind-tunnel model of Northrop Alpha with "pants-type" (or trouser) gear. (From wind-tunnel archives, California Institute of Technology, courtesy of Gerald Landry.)

reporting on design progress on the Alpha to a technical advisory committee of United Aircraft, he indicated further that "a retractile [*sic*] gear is being designed to be incorporated later." (Terminology, as well as type of gear, had yet to be standardized.) Though events themselves were complicated, use of retractable gear was clearly Northrop's intention ultimately for the Alpha.[10]

By mid-1930, his ideas were evidently changing. In May, in a second report to the advisory committee, he mentioned, not only the "retractile" gear, but a new "pants-type" gear as well. To assess this carefully streamlined fixed gear, Northrop had wind-tunnel tests conducted in late 1930 on a model of the Alpha (fig. 4) at the California Institute of Technology. Also tested for comparison were the existing tripod gear and a streamlined underwing enclosure to stow a retracted gear. Caltech's Clark Millikan and Arthur Klein, reporting on the tests, noted a large reduction in drag for both the enclosure and the pants-type gear. They expressed "surprise," however, that the pants-type gear proved almost as beneficial as retraction into the enclosure. These results were apparently crucial in influencing Northrop to

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[10] Northrop, p. 645; A. S. Menasco, "The Founder's Story" (speech to the Management Club, California Division, Menasco Manufacturing Co., January 29, 1969; reprinted by the company, n.d.); "Report of Second Meeting, Technical Advisory Committee" (United Aircraft & Transport Corp., Seattle, December 2–6, 1929).

adopt the pants-type gear in place of a retractable design for modification of the Alpha.[11]

For Northrop, as for designers before and since, choice and design of a landing gear involved tension between a number of conflicting requirements.[12] These fall into five categories that (except for the inclusion of weight in certain cases) are common to most devices. They can be listed as follows with application in particular to the landing gear. I assume that the reasons behind them do not call for explanation.

Performance: In addition to being able to withstand the necessary landing loads, the landing gear should cause as little aerodynamic drag as possible.
Weight: As with all components of an airplane, the landing gear should be as light as possible.
Initial Cost: Cost of design, materials, and manufacture should be minimized.
Reliability: If retractable, the gear should fold and extend with rare malfunctions.
Maintenance: The gear should be maintainable in working order in routine operation with a minimum of time and expense.

(The various aspects of a possible category of *operating costs* I take to be subsumed under performance and maintenance. An unavoidable element of arbitrariness exists in any classification of this sort.)

If aerodynamic performance—that is, reduction of drag—were the sole consideration, the retractable gear, which eliminates landing-gear drag entirely, would be the immediate, obvious choice. It is in this sense that the usual view sees such gear as the "ideal solution." In fact, the additional requirements cannot be ignored. With regard to performance in relation to weight, a retractable gear invariably weighs more than a well-designed fixed gear for the same situation, and this weight must be supported by an increase in lift. Producing

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[11] "Report of Third Meeting, Technical Advisory Committee" (United Aircraft & Transport Corp., Hartford, Conn., May 19–23, 1930); C. B. Millikan and A. L. Klein, "Wind Tunnel Tests of Modifications to 1/6th Scale Model of Northrop Alpha Airplane," GALCIT Report no. 102 (California Institute of Technology, Pasadena, December 30, 1930). The tests were among the first in Caltech's new 10-foot tunnel. In the report to the United Aircraft technical committee in May, Northrop had reported that, when completion of the Caltech tunnel was delayed, models had been sent for test to New York University. I am unable to find reports of these tests.

[12] For a brief contemporary textbook discussion of such requirements, see C. C. Carter, *Simple Aerodynamics and the Airplane,* 4th rev. ed. (New York, 1932), p. 191. For considerations in the design of landing gear before retraction was adopted, see W. L. Smith, *Air Transport Operation* (New York, 1931), pp. 149–55.

this lift in turn creates drag that tends to offset the gain from retraction. The resulting trade-off can be calculated on the basis of theoretical equations well understood in Northrop's time.[13] Knowledge about cost, reliability, and maintenance, however, can come only from experience with construction and operation of a new gear when the design departs appreciably from the normal. Designers have to project such matters as best they can, but their projections are unavoidably fallible. As with most engineering problems in the real world, the overall task is complex.

Evidence suggests that Northrop was alert to all these considerations. Whether he in fact calculated the trade-off between weight and performance is impossible to say—design analyses of this sort rarely survive for long. Writing to Jack Frye, operations chief for TWA, he did say regarding the modified Alpha that "both take-off and cruising speeds were appreciably better in our tests in spite of the additional load of 350 lbs. used with the new [i.e., pants-type] gear." Concern for cost, reliability, and especially weight is implicit in a statement, in his previously mentioned article on the "flying wing," that design of a retractable gear "is exceedingly difficult due to the high [landing] loads involved." The interrelated demands of all five requirements (cost, reliability, and maintenance subsumed in effect under "simplicity") appear in the following passage from a Northrop sales brochure from a few years later: "Carefully developed streamlining provides an aerodynamic efficiency in the Northrop gear almost equal to full retraction but with greater simplicity and much less weight." A second brochure contains a full paragraph detailing the maintenance virtues of the Northrop gear.[14]

Northrop, however, had a special concern, stemming from the additional fact that a retractable gear needs space for stowage when retracted. According to an interview with the prominent designer Edward Heinemann, who worked as a young engineer on the Alpha, he—Northrop—was uneasy about the effect of this requirement on his innovative wing structure. Providing space to stow the retracted gear inside the low wing—the aerodynamically preferred place to put it—would require interrupting the multicellular arrangement, and Northrop was reluctant to do this. He had gone to great effort to keep

[13] For the necessary basic equation, see, e.g., eq. (6.28) in J. D. Anderson, Jr., *Introduction to Flight* (New York, 1978), p. 220. This equation must be corrected for an obvious algebraic typographical error.

[14] J. K. Northrop to J. Frye, August 18, 1931, wind-tunnel archives, California Institute of Technology; Northrop, "The All-Wing Type Airplane," p. 645; "Northrop Delta Model" (sales brochure, Northrop Corp., undated, probably ca. 1934); "The Northrop Long Range Bomber" (sales brochure, Northrop Corp., undated, probably ca. 1936).

FIG. 5.—Northrop Beta. (Courtesy of Northrop Corporation and Ira E. Chart.)

the structure light and simple, and providing sufficient strength in the presence of such interruption might compromise this achievement. The fact that the prospective stowage space tested at Caltech took the form of a streamlined enclosure under the wing supports this contention. When the Caltech tests showed the pants-type gear to give almost as much drag reduction as would retraction into this enclosure, Northrop's course was presumably clear. A carefully streamlined pants-type fairing over a relatively light, tubular, load-carrying structure gave him a reliable, low-drag, easily maintained, low-cost landing gear that did not require compromising the wing structure.[15]

As it happened, the pants-type gear appeared first, not on the Alpha, but on the Northrop Beta (fig. 5) in April 1931. This elegant two-seat sport monoplane, for a complex of reasons, never went into production.[16] After further encouraging tests at Caltech in the early summer,[17] the pants-type gear—now and subsequently called a "trouser" gear—was installed on existing Alphas starting in September.

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[15] Author's interview with E. H. Heinemann, Rancho Santa Fe, Calif., March 12, 1991.

[16] A second prototype Beta was built with a single cockpit and radial air-cooled engine. The project was not pursued, however.

[17] A. L. Klein and C. B. Millikan, "Wind Tunnel Tests of a 1/6th Scale Model of a Northrop Alpha Airplane with Various Fillets and Other Modifications," GALCIT Report no. 103 (California Institute of Technology, Pasadena, July 27, 1931).

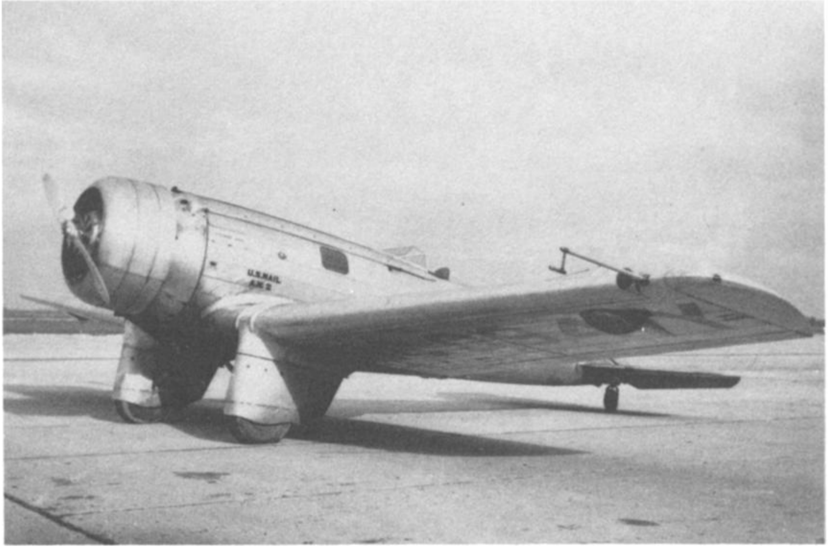

FIG. 6.—Northrop Alpha, mail version, modified to incorporate trouser landing gear. (Courtesy of Richard S. Allen.)

Ultimately, all of TWA's Alphas had their original tripod gear similarly replaced, some at the Northrop factory in southern California and some by TWA in its shops at Kansas City. The last of the seventeen Alphas that were built (fig. 6) carried mail on TWA's routes for most of four years. The sole Alpha remaining today hangs, in the company of two other key aircraft of the airframe revolution (Boeing 247 and Douglas DC-3), in the National Air and Space Museum in Washington, D.C.

The landing-gear decision behind him, Northrop used the trouser gear without question on succeeding airplanes. The Northrop Gamma (fig. 7), which first flew in late 1932, attracted admiration as one of the sleekest and most advanced aircraft of its day. Along with the Lockheed Orion, it pioneered the use of wing flaps for landing and takeoff. Northrop laid out the initial Gamma, the *Texaco Sky Chief* shown here, for the record-setting, advertising-minded flier Frank Hawks, though he probably had airmail use in mind as well. The Northrop Delta, a nine-place passenger-carrying airplane with a larger-diameter fuselage but the same basic layout as the Gamma, appeared in mid-1933. Figure 8 shows the landing gear on a Delta, with a portion of the fairing removed for maintenance of the structure, shock absorber, and wheels.[18] The Gamma *Polar Star* used

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[18] Northrop sales brochures (n. 14 above); "The Northrop Delta," *Aero Digest* 23 (December 1933): 28–29, 31.

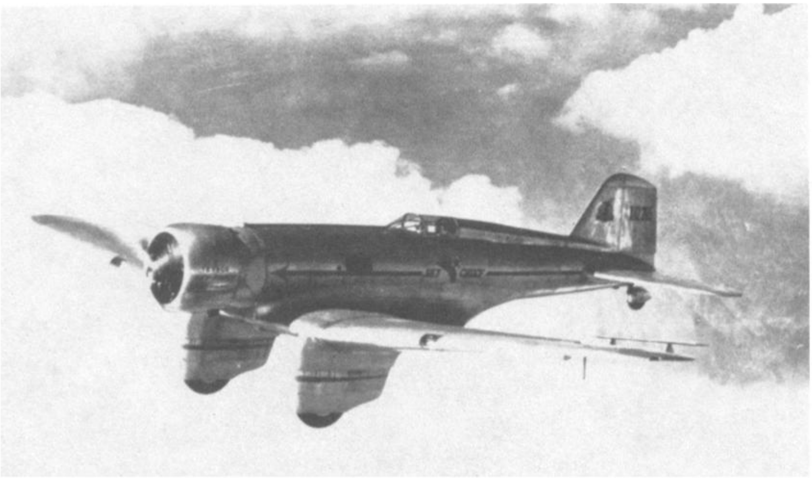

FIG. 7.—Initial Northrop Gamma, *Texaco Sky Chief,* built for Frank Hawks. (Courtesy of Northrop Corporation and Ira E. Chart.)

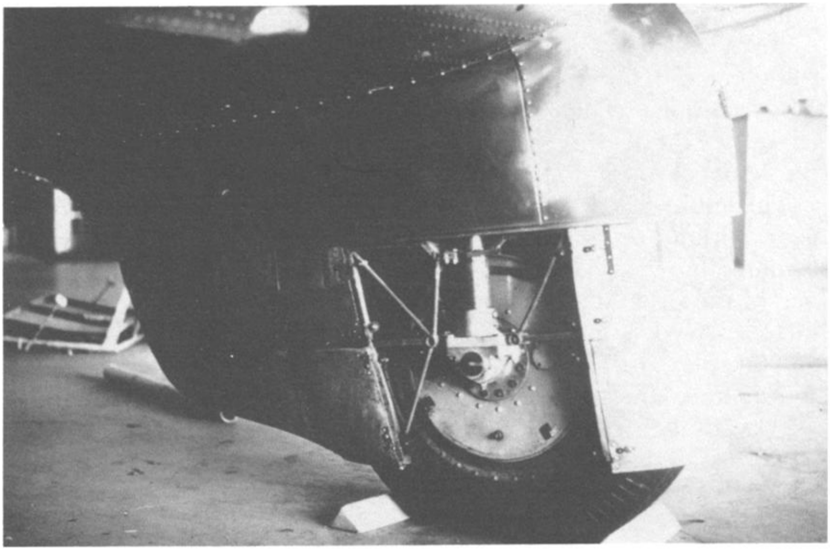

FIG. 8.—Trouser landing gear of Northrop Delta, fairing removed for maintenance. (Courtesy of Richard S. Allen.)

by Lincoln Ellsworth in his trans-Antarctic exploration flight of 1935 also resides in the Air and Space Museum.

The Gamma and Delta, in various modifications for a number of purchasers, competed successfully with their contemporaries in the airframe revolution. In the hands of Hawks, Frye, and Howard Hughes, Gammas set transcontinental speed records from Los Angeles to New York from 1933 to 1936. The cruising speed of around 190 miles per hour (mph) for both airplanes kept pace with the 190–200 mph of the DC-1, which appeared in the same year as the Delta. The Gamma and Delta gave little, if anything, away in performance to their contemporaries with a retractable gear.

The last Northrop craft to use the trouser gear was the XFT-1, a small fighter designed for the U.S. Navy and completed early in 1934. Wind-tunnel tests at Caltech showed a relatively high proportion of landing-gear drag, owing to the large size of the gear relative to the small overall airframe.[19] Despite this fact, the airplane showed the highest speed of any navy fighter of the time. Poor spin characteristics worked against it, however, and only the prototype was built.

Following the XFT-1, Northrop began apparently to see the trade-offs differently. From 1934 to 1937, he and his designers—including Heinemann, who was becoming increasingly Northrop's right-hand man—went over gradually to retractable gear. The transition extended over a number of adaptations of the Gamma for use by the military services. It included several forms of backward retraction of the wheels into vertical, faired pods beneath the wing (based on wind-tunnel tests at Caltech) and finally—on the A-17A army attack plane—retraction laterally inward into a horizontal, completely flush enclosure at the juncture of the fuselage and the leading edge of the wing. These arrangements all managed to avoid interrupting Northrop's multicellular wing structure. Details of the events were complex and need not concern us here.[20]

Northrop's thinking in moving away from the trouser gear can only be conjectured. Thanks to airframe innovations and increasing engine power, flight speeds were going up. The theoretical equations

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[19] C. B. Millikan and A. L. Klein, "Wind Tunnel Tests on a Model of the Northrop XFT-1 Navy Fighter Airplane," GALCIT Report no. 123 (California Institute of Technology, Pasadena, July 13, 1933).

[20] Allen, *Northrop* (n. 6 above), pp. 94–97, 100, 105–6; R. Wagner, *American Combat Planes*, 3d ed. (New York, 1982), pp. 164–66, 354–55; C. B. Millikan and A. L. Klein, "Wind Tunnel Tests on a 1/6th Scale Model of the Northrop XBT-1 (Class VSB-VB) Single-Engine Monoplane," GALCIT Report no. 141 (California Institute of Technology, Pasadena, October 18, 1934).

indicate that, as speed increases, the drag penalty from carrying the additional weight of the retractable gear becomes progressively smaller relative to the gain from retraction.[21] This shifting trade-off doubtless had influence. At the same time, experience with cost, reliability, and maintenance was being accumulated—demonstrably encouraging in the case of reliability (see below)—and engineers were becoming more ingenious in their structural and mechanical designs. For Northrop, this ingenuity included ways to avoid compromising his multicellular wing structure. All these things could have influenced him to move into what the usual view sees as the obvious mainstream of development.

In the context of the usual view—that introduction of the retractable landing gear was a foresighted progression toward an essentially preordained outcome—the Northrop episode does seem a curious anomaly. Northrop's persistence with a fixed gear looks to be a temporary deviation from an engineering mainstream, a consequence, in part, of concern for his new multicellular wing structure. That, at least, is how things appeared until I dug deeper into contemporary events. The "anomaly" interpretation, I soon realized, oversimplifies the historical context.

A More General View

The oversimplification becomes apparent from two bodies of evidence: the airplanes and research efforts of the time and the writings of contemporary engineers. To go fully into these matters would be part of the book imagined in the introduction. The following overview, I believe, covers the essentials.

As one can see from the annual volumes of *Jane's All the World's Aircraft,* the years 1928–35 witnessed a remarkable variety of landing gear on American airplanes. Besides the key airplanes already mentioned from the airframe revolution,[22] retractable gear showed up on a diversity of craft. Examples include (among others) the four-place low-wing Alexander Bullet (1929); two military biplanes, the Grumman FF-1 (1931) and Curtiss YO-40 (1932), the former with gear retracting into the side of the fuselage instead of the wing; and a commercial biplane, the Beechcraft B-17-L (1934). Especially characteristic of the diversity were two commercial airliners: the single-engine low-wing Vultee V-1 (1932), at 215 mph cruising speed probably the fastest airplane in the group, and the twin-engine biplane Curtiss Condor (1933), at 145 mph one of the slowest. This

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[21] See n. 13 above.

[22] See text and n. 3 above.

range suggests that introduction of retractable gear was hardly a considered progression.[23]

Other airplanes besides Northrop's used trouser gear. These included the Curtiss A-8 (1931) and A-12 (1933) military attack monoplanes, the Beechcraft predecessor (1932) of the biplane mentioned above, and the Seversky Sev-3 (1934), the first of two carefully streamlined Seversky monoplanes with such gear. Even the Boeing Monomail, which appeared initially in 1930 with retractable gear, was tested for comparison equipped with trouser gear. (No final decision was made since the airplane never went into production. Subsequent Boeing designs, however, favored retraction.) All these arrangements were different in detail from Northrop's and from each other, and may well have been arrived at independently—evidence on this point is hard to come by.[24]

All through the period, airplanes also appeared with fixed gear incorporating so-called wheel pants (streamlined fairings enclosing the wheels; fig. 9); even a representative sample would be impractical here. One designer, the noted Giuseppe Bellanca, touched all bases; his various aircraft of the period exhibited unstreamlined fixed gear, wheel pants, trousers, and retractable gear.[25] Bellanca and his contemporaries appear to have been trying everything they could collectively think of. (Attention here has been limited to commercial and military planes. Racing planes will be mentioned later.)

Research on landing gear from the National Advisory Committee for Aeronautics reflected similar diversity. After noting the potential aerodynamic gains from retraction and the increasing use of retractable gear, the committee's *Annual Report* for 1933 also stated that "the use of nonretractable gears in several high-performance airplanes indicates the need for more information on the possibilities" with fixed gear. This need, along with measurements on certain partly retractable arrangements, was addressed in wind-tunnel tests by research engineers at the committee's Langley Field laboratory; the

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[23] *Jane's All the World's Aircraft,* various eds. (London), passim; see also Wagner, passim; and J. P. Juptner, *U.S. Civil Aircraft,* 9 vols. (Los Angeles and Fallbrook, Calif., 1962–81), passim. Information in the next two paragraphs comes also from these sources. John Kimball (*Freedom to Soar* [Mountain View, Calif., 1989], p. 11) states that Northrop provided a "fully retractable landing gear" on a Gamma for the prominent flier Jacqueline Cochran. I am unable to confirm this statement in Cochran's or Northrop's writings or elsewhere.

[24] Trouser gear (using skids instead of wheels) appeared as early as 1920 at the Wasserkuppe glider meetings in Germany on the *Black Devil* glider of the noted designer Wolfgang Klemperer; A. Welch and L. Welch, *The Story of Gliding* (London, 1965), pp. 51–53.

[25] R. Deering, "The Bellanca Story, Part II," *Sport Flying* 2 (August 1968): 42–57.

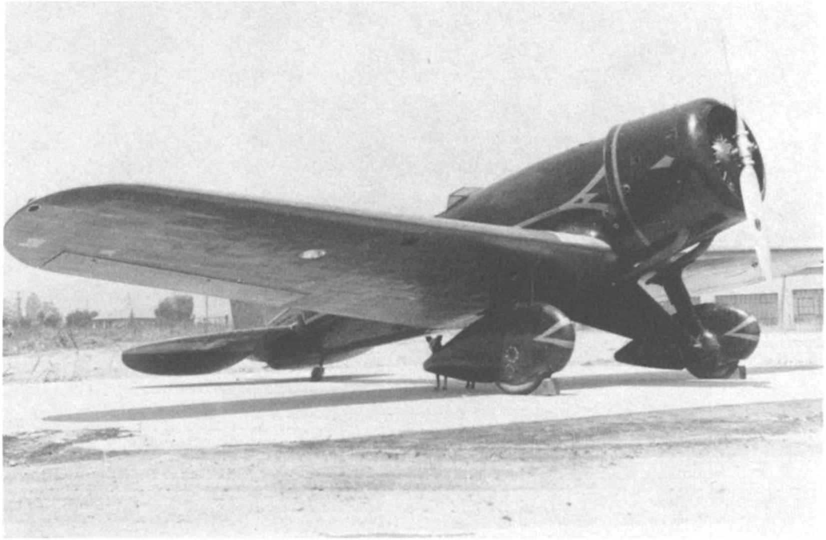

FIG. 9.—Lockheed Sirius built for Charles A. Lindbergh, showing typical example of wheel pants. (Courtesy of Richard S. Allen.)

results appeared in three reports published in 1934–35 under the common title "The Drag of Airplane Wheels, Wheel Fairings, and Landing Gears." The first report alone covered tests of twenty-two different fixed landing gear in a total of fifty-five modifications. A Northrop-type trouser gear proved to have the lowest drag. Calculations based on the results showed that on a hypothetical, aerodynamically clean monoplane with a top speed of 210 mph, replacement of the trouser gear by a fully retractable gear would increase the speed by 8.6 mph.[26] The report judged that "Whether or not the . . . increase in speed due to a retractable gear . . . is worth the design and structural complications in all cases is a question that can be solved only by the designers of airplanes."[27] As we have seen from their products, that is what designers, in effect, were trying to do.

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[26] Some tests of airplanes with retractable gear (e.g., S. J. DeFrance, "The Aerodynamic Effect of a Retractable Landing Gear," Technical Note no. 456 [NACA, Washington, D.C., 1933]) reported reductions of minimum drag by as much as 50 percent with gear retracted. Such comparisons are highly misleading, however, because no effort was made to streamline the extended gear in such situations.

[27] *Nineteenth Annual Report of the National Advisory Committee for Aeronautics, 1933* (Washington, D.C., 1934), p. 10; W. H. Herrnstein, Jr., and D. Biermann, "The Drag of Airplane Wheels, Wheel Fairings, and Landing Gears, Part 1, Part 2: Nonretractable and Partly Retractable Landing Gears, Part 3," Report nos. 485, 518, 522 (NACA, Washington, D.C., 1934, 1935, 1935), quotation from part 1, p. 9.

Writings in engineering publications suggest the considerations going through designers' minds. In his magazine article on the "flying wing" quoted earlier, Northrop, after noting the theoretical gains from mechanical retraction, added: "but a tremendous amount of thought has been given to the problem and it still remains essentially unsolved." John G. Lee of the Chance Vought Corporation, in an article on the "Relation of Design to Airplane Maintenance" in the *SAE Journal* in 1932, likewise described the landing-gear problem as "now being fought out." He observed that "no absolutely reliable retracting mechanism has really been designed," that "maintenance problems . . . with a retractable gear are severe," and that "the whole situation may be regarded as strictly experimental." Frank T. Courtney, a consulting test pilot writing on "Air-Transport-Design Economy . . ." in the same journal and year, also viewed the retractable gear skeptically. In his view, the structural economy of a fixed gear doing double duty as part of the supporting structure for an externally braced wing might "lead to at least as great over-all efficiency . . . , with an additional saving in maintenance." And even as knowledgeable a figure as Hall L. Hibbard, assistant chief engineer (later chief engineer) at Lockheed, in a general review of "Problems in Fast Air Transport Design" in *Mechanical Engineering* in 1933, expressed doubts. Despite his company's two years of success with retractable gear on the Orion, Hibbard still saw "some question as to the advisability of the retractable gear from the standpoint of speed increase." He based this opinion on "careful wind tunnel tests" (otherwise unspecified) of fixed gear of the "pure cantilever type . . ., similar to that pioneered by Northrup [*sic*]."[28]

Textbook writers expressed similar sentiments. Wesley L. Smith in his 1931 book on *Air Transport Operation,* put forth the opinion, as in Northrop's flying-wing article, that the problem of the retractable gear "has not yet been satisfactorily solved." C. C. Carter, in his popular aerodynamic textbook of 1932, noted use of retractable gear on the Boeing Monomail and B-9 bomber and discussed the weight, reliability, maintenance, and stowage problems of such gear. Because of these problems, and despite its obvious aerodynamic advantages, the retractable gear, he asserted, "has not been regarded favorably by the Air Corps." Although the device might prove necessary someday, he "felt that such a development is in the distant future. Improvements

[28] Northrop (n. 5 above), p. 645; J. G. Lee, "Relation of Design to Airplane Maintenance," *SAE Journal* 31 (October 1932): 412–20, quotations on 418; F. T. Courtney, "Air-Transport-Design Economy and Air-Transport Testing," *SAE Journal* 31 (September 1932): 356–60, 377, quotation on 358; H. L. Hibbard, "Problems in Fast Air-Transport Design," *Mechanical Engineering* 55 (October 1933): 611–17, quotations on 614.

in [fixed] landing gear design with consequent reduction of parasite resistance [i.e., drag] may meet every requirement." In thus anticipating what Hibbard would say the next year, Carter may or may not have had Northrop's trouser gear in mind.[29]

Uncertainty about reliability, in particular, appeared in both airplanes and writings. Lee could still make his quoted statement about the lack of a "reliable retracting mechanism" despite experience since the mid-1920s with (mostly externally) retractable gear on amphibian aircraft, such as designed by Grover Loening and Igor Sikorsky. (This experience will need to be assessed in any full history of landing-gear retraction.) The Boeing Monomail gave evidence of fears about what might occur if malfunction of the mechanism forced a landing with gear retracted; the drawn-up wheels (see fig. 1) were made to protrude below the wing to cushion the impact and ensuing slide. On the other hand, experience with the Lockheed Orion (fig. 2), which had wheels that disappeared flush inside the wing, suggested that such fears might be uncalled-for; Hibbard in his article of 1933 reported six wheel-up landings with no injuries to occupants and only minor damage to the airplane. Thus, "instead of being dangerous, retractable gears have become a safety feature [for emergency landings on questionable natural terrain] and transport operators are demanding them from that standpoint." Uneasiness about reliability apparently persisted, however. The DC-1, which was designed by Douglas to meet the requirements of TWA, appeared in the same year as Hibbard's article, with its retracted wheels protruding below the engine nacelles. This feature appeared also on the DC-2 and -3 (though it vanished from the scene as time went by).[30]

Within the world of landing gear, the context for Northrop's trouser design was thus hardly simple or certain. Though the purely aerodynamic advantages of retraction could not be doubted, the ultimate solution in a practical engineering sense that took account of all requirements appeared far from clear. The landing-gear problem, moreover, occurred within similarly diverse and uncertain environments of experimentation concerning propellers, wing flaps, metal construction, and improved engines.[31] Engineers in the opening years

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[29] Smith (n. 12 above), p. 149; Carter (n. 12 above), p. 191.

[30] For Loening and Sikorsky amphibians, see Loftin (n. 4 above), pp. 183–87; and G. Loening, *Amphibian: The Story of the Loening Biplane* (Greenwich, Conn., 1973), pp. 14–15, passim; quotation from Hibbard (n. 28 above), p. 614; for photos of DC-1 and -3 with wheels retracted, see Miller and Sawers (n. 3 above), opposite pp. 112 and 113.

[31] For an excellent summary of the overall "environment of innovation," see Miller and Sawers, pp. 50–51.

of the 1930s agreed in their goal of higher speeds; their crystal ball for how best to get there, however, was unavoidably clouded.

Airplanes today exhibit different kinds of landing gear in an ordered way, and the topic no longer arouses discussion. Fixed gear, either unstreamlined or with wheel pants, predominate at low speeds and retractable gear at high, with the changeover occurring around 200–250 mph. (The fact that aircraft in the first half of the 1930s were moving into this range may have helped foster the observed diversity.) When very low drag is at a premium at low speeds, as on sailplanes, retractable gear do appear, but the exception is a minor one. Trouser gear like Northrop's are apparently not found worth the trouble anywhere. The complex variety observed in our account has long been a thing of the past.

How the present situation came into being after 1935 would need examination in the imagined book. That it did not happen immediately is suggested by the following contrast regarding racing planes: The Hughes H-1 monoplane, in which Howard Hughes set a landplane straightaway speed record of 352 mph in 1935, had a highly refined retractable gear. As late as 1938, the Thompson Trophy Race, the blue-ribbon event of American closed-course racing, was won at 283 mph by a Turner Laird racer with fixed gear incorporating wheel pants.[32] Other examples for both racing and nonracing planes could easily be cited, both in the United States and abroad.

A further matter warrants recording here, lest it be overlooked. The earliest retractable gear were designed to be raised and lowered by slow and laborious hand cranking by the pilot. In later gear, the task was taken over by an electric motor or, more commonly—for reasons of weight in relation to the required power—by a hydraulic cylinder. Unfortunately, the latter solution raised another difficulty; the sliding leather packings used to seal the piston of the hydraulic actuators tended to leak fluid, causing troublesome and costly problems of maintenance. Solution of this problem came with introduction at the start of the 1940s of the hard-rubber O-ring, invented by Niels Christensen in 1933 and patented in 1937. The success of this timely device, which is used in the millions in all kinds of applications today, depends critically on the proportions of the straight-sided groove that houses the doughnut-shaped ring. The importance of the O-ring for retractable gear was pointed out to me by Ed Heinemann, who took over design responsibility when the second Northrop company became the El Segundo Division of Douglas in 1937 and Northrop

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[32] *Jane's All the World's Aircraft, 1935* (n. 23 above), p. 311c; C. Caldwell, "Review of the National Air Races," *Aero Digest* 33 (October 1939): 34–35, 153, photo on 35.

resigned to form his third company. Heinemann went over entirely to a flush, inwardly retracting gear on the Douglas SBD-series of dive bombers, which he developed based on earlier Northrop-company designs. He said, however, that he did not feel completely comfortable with retractable gear until the O-ring appeared and that other designers felt the same. Thus did a seemingly minor component play an important role in the success of a much larger and more visible device. This kind of situation may be present invisibly in many cases.[33]

What, then, can we say by way of answer to our question from the introduction? Certainly—and contrary to my earlier supposition—to recast the question in terms of an aberration from a rationally self-evident path misreads the issue. To the design community at the time, retraction was far from "so clearly the way to go." Northrop's trouser gear, conspicuous for a while, was in no way an anomaly in an otherwise linearly ordered pattern (hence the quotation marks in this article's title). Designers experimented with various kinds of fixed gear along with retraction, and the outcome seemed far from preordained at the time. I shall contend later that the retractable gear had a kind of technical imperative in light of the large, overall increase in speed that a combination of advances would eventually open up—no high-performance airplane is imaginable today without it. Designers in the early 1930s, however, lived in a world of small, progressive speed increments coming from loosely related changes in various components of the vehicle. Northrop, when he adopted the trouser gear, did not see it as a stopgap measure. Hall Hibbard, despite encouraging experience with retractable gear at Lockheed, did not regard his competitor's solution as misconceived or unpromising for development. The community of designers was feeling its way into the future in a state of knowledge in which engineering assessment was, at best, problematic. The technical imperative of the retractable gear is knowledge after the fact. We see the outcome; designers at the time, by their own testimony, did not *fore*see it.

Having said that, we can return to the original question. The events we have traced, however, suggest that it be broadened: how was it that Northrop—and his fellow designers—proceeded as they did in adopting retraction? The answer to this question, which emerges also from our account, has general implications for the processes of learning

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[33] This paragraph depends on information from the following sources: Loening, p. 15; Kimball (n. 23 above), p. 16; G. Wise, "Ring Master," *American Heritage of Invention and Technology* 7 (Spring/Summer 1991): 58–63; Heinemann interview (n. 15 above); Allen, *Northrop* (n. 6 above), p. 157; Wagner (n. 20 above), pp. 355–56. For leather packings, see J. N. Smith, "Design and Materials for Hydraulic Packings," *Aero Digest* 40 (April 1942): 119–22.

and change in engineering. It falls naturally within the framework of the variation-selection model mentioned in the introduction.[34]

Variation and Selection

The variation-selection model, as put forth in the final chapter of my book, grows out of fundamental ideas by Donald Campbell and their initial application to technology by Edward Constant. It is, in Campbell's description, one of *blind variation and selective retention,* a terminology that highlights the two basic elements of the learning process. Though I attempt a brief outline of the model below, a theoretically minded reader may want to consult the book for elaboration.[35]

A detail of semantics, however, needs attention. For Campbell, the modifier "blind" denotes that in any search for knowledge that is truly *new*—that is, not arrived at before—candidate variants must, almost by definition, go "beyond the limits of foresight or prescience."[36] I think of the seeker for knowledge as rather like a blind person trying to reach a desired destination by going down an unfamiliar passageway, using tactile input from a cane and the constraint available from the passage's sidewall. Though the person is not without guidance, whether the passage goes where desired or turns out a blind alley cannot be foreseen; it can be learned only by proceeding along "blindly" (though, note, not "randomly" or "unpremeditatedly" or "unconstrainedly") to the end. Though not without virtues, this use of "blind" causes problems. Some readers seem determined to equate it with "random." Others feel, with some justification, that when applied to technology (or science), it denies the characteristic goal orientation and "directedness" of such activity. As a reader of these materials has pointed out, designers such as Northrop are not entirely blind; they *see* where they want to go and by what means they propose to get there. What they cannot do, if their idea is novel, is *foresee* with

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[34] Theoretical questions about the growth of knowledge and the evolution of artifacts play an increasing role in the study of technology by both sociologists and historians. For argument about the resulting tension for the history of technology, see the article, response, and comment by, respectively, R. A. Buchanan, J. Law, and P. Scranton under the common title "Theory and Narrative in the History of Technology," *Technology and Culture* 32 (April 1991): 365–93.

[35] Vincenti, *What Engineers Know* (n. 2 above), chap. 8; for references to the work of Constant and Campbell, see, in particular, pp. 269 and 316–17. For a general review of evolutionary epistemology, of which Campbell's is one form, see M. Bradie, "Assessing Evolutionary Epistemology," *Biology and Philosophy* 1 (1986): 401–59.

[36] D. T. Campbell, "Blind Variation and Selective Retention in Creative Thought as in Other Knowledge Processes," *Psychological Review* 67 (November 1960): 380–400, quotation on 381.

certainty whether it will work in the sense of meeting all the relevant requirements.[37] To make this distinction clear, I will here describe new technological variants as "unforesighted" rather than "blind." Though less than felicitous, this may avoid distraction from the central argument.

The variation-selection model pertains to both the generation of knowledge and the devising of artifacts (which is itself a kind of generation of knowledge, specifically, of how to arrange and proportion a device to accomplish a given task). It thus applies to both engineering research and engineering design. In the story at hand the concern is mainly with design, though, in the end, knowledge will also be seen to be at issue. The overall model also comprises two rather different phases, the first involving variation and selection and the second mainly selection. Though I describe them here in order, in practice they occur intertwined, and developments go on typically back and forth between them. The phases can be denoted, respectively, as *hidden* and *overt.* (The jargon is regrettable, but the distinctions are fundamental.) As always, both phases were present necessarily in the landing-gear story.

The hidden phase, as the name implies, takes place out of sight in the designer's mind. How imagined variants arise in this phase raises the usual difficult questions about the creative process. In engineering, it presumably includes search of past experience for solutions that have proved useful in comparable situations, mental incorporation of whatever novel features come to mind as desirable in the current circumstances, plus a certain amount of serendipitous mental brainstorming. The selection activity in this phase entails a mental winnowing of the conceived variants to pick out those that seem most promising. Here thought trials and judgment distilled from experience come into play. Though nominally separate, variation and selection in the hidden phase go on concurrently in a more or less disordered way in the designer's mind, much of it probably at an unconscious level. Out of the hidden phase come visible variants for overt examination.[38]

We can only infer, of course, what went through the minds of Northrop and his contemporaries in the hidden phase of their landing-gear work. From his actions and writings concerning the "flying wing," Northrop obviously gave consideration to the gains from retraction. Whether he weighed and discarded the idea of wheel

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[37] E. T. Layton, personal correspondence.

[38] My book (n. 2 above, pp. 244 and 248) identified the hidden phase entirely with variation (except for a minor qualifying observation) and the overt phase with selection. Inclusion of selection also in the hidden phase strikes me now as more sensible.

pants, the evidence does not say. Such thought, likely given the considerable use of that device at the time, could have led to his notion for the more streamlined trouser gear. From the evidence of their airplanes, other designers conceived a variety of variants. Whether they thought of and immediately rejected as harebrained some that we do not even imagine, we most likely will never know. The visible variants that we do know of included trouser gear, retractable gear of various kinds, and a wide variety of gear with wheel pants, some cantilever and some braced, either independently or as part of a wing-support structure.

To the extent that variants from the hidden phase involve novelty, they (as well as those mentally discarded) must be unforesighted in some degree. Activities in the overt phase then seek to deal with this unforesightedness through some kind of visible trial. The designer or design community thus attempts to select from the overt variants those that best (or at least satisfactorily) achieve their goal. The trial may be *vicarious,* through some representation of the artifact, or *direct,* through the artifact itself. These trials also subdivide in turn. Vicarious trial can take place by experiment with models or other reproductions of the artifact or by analytical "tests"—that is, theoretical calculations—on paper.[39] Direct trial can be supplied deliberately by proof test of the completed artifact and will come inevitably through everyday use. Usually in combination, these types of trial provide the means for overt selection.

Northrop and the design community followed such selection procedure as best they could for the landing gear. As we have seen, the trade-off between aerodynamic performance and weight could have been tested vicariously by theoretical calculation. Whether designers actually did so cannot be known. (Given the general level of design sophistication at the time, I am inclined to doubt it.) The relative aerodynamic merits of different overt variants—retraction versus trouser gear—were tested vicariously by experiments conducted for Northrop in the Caltech wind tunnel; other designers may well have done likewise. Assessment of cost, reliability, and maintenance had to come from construction (a kind of trial) and direct trial of the completed device. Such trial was supplied in the course of the proof tests to which the prototypes were necessarily subjected and—especially and rigorously—by the everyday use to which the aircraft were put (witness Hibbard's report of the wheel-up landings with the

[39] For the real sense in which such calculations are "tests," see Vincenti, *What Engineers Know,* p. 248; and H. Petroski, *To Engineer Is Human: The Role of Failure in Successful Design* (New York, 1985), p. 44.

Orion). Largely on the basis of the wind-tunnel trials, Northrop selected trouser gear for his Greek-letter aircraft, a choice that proved short-lived. As experience accumulated from everyday use—and speeds went up steeply from a synergistic combination of engine and airframe innovations—the design community, including Northrop himself, departed permanently from trouser and other fixed gear; using a combination of vicarious and direct trial, it selected retractable gear for the long-term solution.

Unforesighted variation and selective retention thus appear clearly—of necessity, apparently—in the landing-gear story. Designers, coping with day-to-day problems, thought up a variety of solutions in a process that could not help but be unforesighted as to its eventual outcome. No one in the early 1930s, including as prescient an innovator as Northrop, could know how much airplane speeds would increase from other causes or how constructional and operational experience would work out. Through a complex collective process, the design community nonetheless arrived at a solution. By the late 1930s, it had selected the retractable gear for permanent retention.

Within the variation-selection framework, Northrop's trouser gear, far from an anomaly, was part of the necessary learning process. By their unforesighted nature, different variants oftentimes have to be tried. Some will fail outright, some will work well enough for a while, and some may be selected to have a permanent place in engineering practice. All help engineers to learn. When the future is largely unforeseeable, as it always is to the participants, no other way is possible (short of revelation, which engineers cannot count on).

In the end, the variation-selection process produced more than a type of artifact. As airplane speeds continued to increase, the need to reduce drag became overwhelming in the design trade-offs. One can, of course, propel a fixed gear through the air at any speed with sufficient power. The design community learned, however, that, all things considered, the problem is best solved by retraction. The variation-selection process thus provided in the end a piece of fundamental engineering knowledge—that an airplane for the speed range above, say, 250 mph should have a retractable landing gear. This injunction constitutes engineering knowledge in the sense, noted by Herbert Simon, that it describes how an artifact ought to be to perform its task (in contrast to scientific knowledge, which describes how something innately is).[40] Though engineers nowadays take it for granted, it had to be learned at some time.

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[40] H. J. Simon, *The Sciences of the Artificial*, 2d ed. (Cambridge, Mass., 1981), pp. 132–33.

Looked at from the present-day realization that drag turned out to be determinative, the injunction for retractable gear can be seen to embody a kind of technical imperative (or logic).[41] Such an imperative, however, though real in light of the eventual increase in flight speeds, was not evident to designers at the time, who could not foresee for sure how far airplane development would lead or how the nonaerodynamic requirements would work out. That is not to say that certain people did not anticipate the outcome earlier than others. Research and design engineers can be found in the early 1930s, I am sure, who thought and stated that adoption of retractable gear was inevitable. Esteem for heroes, however, should not cause us to neglect or gloss over the necessity for and nature of the variation-selection process—would-be prophets do not always turn out to be correct. I recall that circa 1970 some capable and experienced engineers held the view, on apparently rational grounds, that the rotary internal-combustion engine (the Wankel engine) would replace the piston engine for much automotive use. Because of air pollution and other practical problems that were not foreseen and had to be found through trial, things have not worked out that way. Today the views are forgotten, and the engine finds little application. That the prophets for retractable gear were more prescient than those for the rotary engine is true, but we see this after the fact. Since engineers had never been down either passageway before, neither group could foresee for sure what the outcome would be. If today we see the retractable gear as having a technical imperative, it is because of the learning process the design community went through.[42]

As illustrated by the landing-gear story, the variation-selection process serves for two sorts of problems, *specific* and *generic*. Northrop used the process in selecting his trouser gear from the variants that occurred to him and, later, in shifting to retraction; he did so to solve specific problems for particular airplanes. The design community followed the process to find out whether high-speed airplanes as a whole ought or ought not to have retractable gear; by doing so it solved a generic problem for a class of aircraft. In the generation of

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[41] For discussion of the internal logic of technology, see Vincenti, *What Engineers Know* (n. 2 above), p. 204.

[42] Bernard Carlson and Michael Gorman put forward an alternative and illuminating framework from their continuing studies of the particular activity of invention (W. B. Carlson and M. E. Gorman, "Understanding Invention as a Cognitive Process: The Case of Thomas Edison and Early Motion Pictures, 1888–91," *Social Studies of Science* 20 [August 1990]: 387–430). Though I have not thought the matter through carefully, I suspect that their formulation and the one in this section are complementary rather than opposed.

variants for both sorts of problems (the selfsame variants in fact serve both), the work of individuals is central—every variant must originate from the mind of an individual, even when that individual is part of a closely knit design team. In selection, at least in the crucial overt phase, matters are different. Here, for a specific problem, an individual or design team still suffices to make the necessary choice. For a generic problem, however, such choice can come about only through replication, over time and in a number of specific cases, of the same decision by a cumulation of designers. The locus of selection for the generic solution must thus lie in the design community.[43] The exact nature of the process, which makes the solution part of normal engineering practice, may be difficult to sort out in a given case. As we have seen for the retractable landing gear, however, it takes place as a communal activity.[44]

The Shaping of Technology

The preceding section, like the material in my book, looks at the mechanics and (to some extent) the technical considerations involved in the variation-selection process. A full examination must involve social considerations as well. This raises the kinds of issues discussed by sociologists and historians in recent years under the heading of the social shaping (or construction) of technology.

Readers of *Technology and Culture* will be aware of the social-shaping point of view from citations of *The Social Construction of Technological Systems,* a volume of articles edited by Wiebe Bijker, Thomas Hughes, and Trevor Pinch. I also find useful a recent overview entitled "The Social Shaping of Technology" by Robin Williams and David Edge. Williams and Edge see studies under the social-shaping rubric as stemming from the realization that "new technologies [involve] a set of choices between different technical options" and that "'social' factors, as well as narrowly 'technical' considerations, affect which options are selected." These remarks clearly imply a variation-selection process, an identification made explicitly by Pinch and Bijker in an article in the aforementioned volume (though neither source employs variation-selection terminology or formalism). Williams and Edge go on to see social shaping as bearing on three essential aspects

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[43] A related difference is that special circumstances, like Northrop's concern for his multicellular wing structure, are likely to have a greater role in specific than generic solutions.

[44] The process here is an example of what social-constructivist writers (whose work will figure in the next section) refer to as "closure" and "stabilization." See W. E. Bijker, T. P. Hughes, and T. J. Pinch, eds., "Introduction" to *The Social Construction of Technological Systems* (Cambridge, Mass., 1987), pp. 9–15, esp. pp. 12–13.

of technology: the *direction* of technological innovation, the *form* of technological artifacts, and the *outcomes* for society of technological change. It is the first two concerns that occupy us here. The landing-gear example speaks explicitly to the question of form and implicitly to the question of direction.[45]

In shaping of form, the design process is central. Decisions taken in design, in both variation and selection, fix the features of the artifact—how it operates, how it is arranged, and what is called for in the shop drawings from which it is built. The place to discern the shaping of technological form, therefore, is in the considerations on which design decisions depend. Do such considerations in a given case stem primarily from social or technical concerns or some combination of both?

To address this question in the landing-gear story, decisions there can be summarized as follows: Design of a landing gear depends on knowledge of the projected weight, landing speed, and general arrangement of the airplane, which are set at the levels of project definition and conceptual design for the overall vehicle. The landing gear must conform to these fixed constraints. Within such specifications, the looser constraints of aerodynamic drag, weight, cost, reliability, and maintenance are subject to trade-offs (on technical grounds if the designer is wise). Given such considerations and the level of flight speed anticipated for their airplanes, designers in the early 1930s opted for a variety of gear, some fixed and some retractable. With the added constraint of his multicellular wing, Northrop saw the trade-offs differently from most and decided on trouser gear. As time went by and speeds increased from other causes, he changed his assessment and went over to retraction. In the end, with accumulation of experience with weight, cost, reliability, and maintenance (including introduction of the O-ring), the design community, including Northrop, made a collective decision that, all things considered, the landing gear of a high-speed airplane should retract if the vehicle is to perform as desired.

Few, if any, social considerations figure in these decisions. It may be tempting to see Northrop's unease at cutting into his multicellular wing as emotional and thus "social," but the evidence points to a hard-headed concern for structural weight. Reliability and maintenance

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[45] Bijker, Hughes, and Pinch, eds.; R. Williams and D. Edge, "The Social Shaping of Technology: A Review of UK Research Concepts, Findings, Programmes and Centres," in *Verbund Sozialwissenschaftliche Technikforschung* (Berlin, 1991), pp. 152–205, esp. pp. 153 and 155; T. J. Pinch and W. E. Bijker, "The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other," in Bijker, Hughes, and Pinch, eds., p. 28.

might be defined in a tenuous sense as "social," but engineers experience them as just as much technical as weight and aerodynamic performance. Cost, an economic and thus a social factor, may have had influence in specific cases early on; it shows no evidence of being a serious problem, however, and apparently played no role in the generic decision for retraction. Nothing appears either of the kinds of concerns that Pinch and Bijker find in different social groups involved in the variation-selection process leading to the normal configuration for the bicycle in the late 1800s—antagonism to the device, alternative societal uses, moral conflicts, attitudes toward and requirements of the sexes, and so forth. One looks also in vain for what those authors call "interpretive flexibility," that is, the different ways that different social groups think of or construe the device, which can play a role in design decisions.[46] To designers, as well as users of the device, the landing gear was simply a means for getting the airplane on and off the ground, and that was that. I think it fair to conclude that social considerations had little or nothing to do with shaping the form of the solution to the landing-gear problem.

Not so with regard to direction. A prime consideration pushing designers in the course they took was clearly the value put on speed by modern society, both to get people from place to place as quickly as possible and to maximize return on capital invested in the vehicle. Speed also has its obvious military uses. The direction of the variation-selection process leading to retractable gear was thus socially shaped. Once the direction had been set, however, technical considerations took over in shaping the form of the outcome, that is, in leading the design community to settle in the end on retraction. The fact that the imperative for retractable gear was not known ahead of time, but had to be learned in the course of the variation-selection process, does not alter this conclusion. For the landing-gear problem of the 1930s, the direction for design was shaped by social considerations; the form of the resulting artifact by technical.

The situation for the landing gear is fairly straightforward. For other devices, it may (or may not) be less so. As I have pointed out elsewhere, for a contrivance like the airplane, which is in reality a complex system, the structure of design is inherently hierarchical.[47]

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[46] Pinch and Bijker, pp. 17–50. These authors also include under interpretive flexibility the different material ways in which an artifact can be designed (i.e., arranged). I think it more realistic and meaningful to regard these as technical possibilities or options rather than instances of "interpretive flexibility" (though the two categories are not completely unrelated).

[47] W. G. Vincenti, "The Scope for Social Impact in Engineering Outcomes: A Diagrammatic Aid to Analysis," *Social Studies of Science* 21 (November 1991): 761–67,

Design of a major component like the landing gear falls at a middle level in the hierarchy. Project definition and overall (or conceptual) design of the vehicle occupy higher levels. (By *project definition* we mean the initiating translation of some ill-defined, usually qualitative need into concrete specifications for the hardware.) Design of a subcomponent, such as a hydraulic actuator for a retractable gear, takes place at a lower level. Such a multilevel, hierarchical relationship, which is typical of complex devices, has unavoidable consequences for designers. Decisions at one level place technical constraints (or requirements) on design at lower levels, and these constraints tend to become more numerous and rigid the farther down the hierarchy one goes; that is, the degree of technical constraint becomes higher.[48] I have argued that, as a consequence, the scope for—and hence likelihood of—social considerations shaping the form of the engineering outcome tend correspondingly to decrease. The retractable landing gear fits this pattern. Indeed, at this middle level of hierarchy, technical considerations took over completely in fixing the form of the solution. The day-to-day interactions of the design community were highly social, as they invariably are. These interactions, however, like the social concerns mentioned earlier, did not generate the considerations on which design decisions depended.[49]

The situation for other airplane components and at other levels of hierarchy invites conjecture. Among the components involved in the airframe revolution, wing flaps and the controllable-pitch propeller would, I suspect, prove much the same as here, as would the stressed-skin aspect of the new aluminum structure. The move to metal itself, however—since stressed skin can be and was accomplished with wood—is a different matter. Eric Schatzberg contends, convincingly I believe, that an existing cultural ideology for the superiority of metal

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and "Engineering Knowledge, Type of Design, and Level of Hierarchy: Further Thoughts about *What Engineers Know* . . . ," in *Technological Development and Science in the Industrial Age,* ed. P. Kroes and M. Bakker (Dordrecht, 1992), pp. 17–34.

[48] Analogous ideas have been expressed in an archaeological context, also, curiously enough, in connection with airplanes: P. Lemonnier, "Bark Capes, Arrowheads, and Concorde: On Social Representations of Technology," in *The Meanings of Things,* ed. I. Hodder (London, 1989), pp. 156–71, esp. p. 168.

[49] In my earlier work (n. 47 above), I explained how the degree of technical constraint increases also as the type of design at a given level of hierarchy changes from *radical* to *normal* (suitably defined). This and the effect of hierarchy can be combined into what I hope is a helpful three-dimensional diagram ("Scope for Social Impact," p. 764). I have not discussed the role of radical-to-normal design here; in view of the absence of social shaping already observed, any differences between landing-gear variants in regard to this role must be insignificant for present concerns.

over wood figured prominently in airplane design.[50] For reasons that Schatzberg traces, objective technical criteria could not dictate the choice of materials—in Schatzberg's words, "the technical evidence favored neither wood nor metal overall." This low degree of technical constraint, in contrast to the situation for retractable gear, gave scope for social considerations (i.e., ideology) to take over. (Cultural bias could not yet have come into being, of course, for such novel things as retractable gear, wing flaps, and controllable-pitch propellers.) In its relation to the degree of technical constraint, the introduction of metal thus fits, in its own way, with the ideas discussed here.[51]

The situation at the levels of project definition and overall design will require study.[52] For the former, as for all levels, the social value of speed obviously shaped the direction of design in the 1930s; so also did a socially motivated desire for increased carrying capacity and therefore size. Even in project definition, however, the resulting specifications (the equivalent here of form) had to be limited by technical considerations of what was realistically possible.[53] In conceptual design, where overall form of the vehicle was set, the situation probably reached greatest complexity. Requirements of structural integrity, high-speed movement in three dimensions, and, most of all, weight—plus the natural hazards of flying—put more numerous and more rigid technical requirements on airplanes than on most devices. These impose severe constraints at all levels of design, including conceptual. In the airframe revolution, changes in middle-level components in the interest of greater vehicle speed and size also influenced conceptual design strongly from below. Such constraint from lower levels is typical in periods of radical change, when the normal configuration for a device is in flux.[54] How much room social shaping could and did have to affect form at the level of conceptual design will need investigation. A full reassessment of the airframe

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[50] E. Schatzberg, "Ideology and Technical Choice: The Decline of the Wooden Airplane in the United States, 1920–1945," *Technology and Culture,* in this issue, pp. 34–69.

[51] Since structure pertains to the entire airplane, structural design can be taken to lie at a higher level of hierarchy than that of a specific component. The change to metal also constituted (see n. 49 above) a definitely radical design departure. A low degree of technical constraint is thus consistent with the diagram cited in that note (though the precise reasons would need examination).

[52] In the early stages of a technological change, levels may not divide so neatly in practice. They can still serve as framework for analysis, however.

[53] "Aspirations" might be more accurate than "specifications" in the instance of a revolution.

[54] For the concept of *normal configuration,* see Vincenti, *What Engineers Know* (n. 2 above), pp. 209–11, 243.

revolution in terms of design decisions and how they were arrived at by the design community offers a worthy project.[55]

For devices less technically demanding than the airplane, the notion of technical constraint suggests that social shaping of form may extend farther down the hierarchy. As indicated earlier, Pinch and Bijker find interpretive flexibility by different social groups playing a central role in shaping the normal configuration of the bicycle (an example at the level of conceptual design). They also make a case that interpretive flexibility regarding purpose had influence in adoption of even such a low-level subcomponent as the pneumatic tire.[56] We can expect as a general trend, I believe, that social shaping of form will diminish in systemic devices as the level of design moves lower in the hierarchy. At what levels and how suddenly the decrease occurs, however, may be very different for different devices. As with the pneumatic bicycle tire, departures from the trend also doubtless exist. Fortunately for historians, the situation is fascinatingly complex.[57]

In light of this complexity—and the findings for the retractable gear—caution may be wise. In the current enthusiasm for the social shaping of technology, we could be in danger of forgetting or downplaying the fact that there is such a thing as technical shaping. Perhaps we should speak of the *technosocial* shaping of technology and visualize the range of considerations in design as a kind of spectrum, with purely social at one end, purely technical at the other, and a varying mixture between. A challenge would then be to assess where in the spectrum a given case falls. To do this, the realities of hierarchy and the distinction between direction of design and form of engineering outcome may be useful. Distinguishing between specific and generic problems may also help.

Epilogue

The Northrop episode and its context thus fall clearly within the framework of the variation-selection model. Northrop, Bellanca, and their fellow designers, struggling with specific design problems (Northrop and presumably others by following their individual

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[55] The statement of Richard Nelson and Sidney Winter regarding continued innovation following the DC-3 could equally well apply to the airframe revolution leading to it: "Engineers had notions regarding the potential of this regime [i.e., combination]." The engineers could not foresee ahead of time, however, just what the combination would contain or where it would lead. See R. R. Nelson and S. G. Winter, *An Evolutionary Theory of Economic Change* (Cambridge, Mass., 1982), p. 259.

[56] Pinch and Bijker (n. 45 above), pp. 28–41.

[57] My book, since it focuses on the epistemology of technical engineering knowledge, may give the impression that I regard all design decisions as being made purely or predominately on technical grounds. If so, the impression is incorrect.

variation-selection procedures), devised trouser gear, wheel pants, and retractable gear. In doing so, they provided at the same time variants for the generic landing-gear problem. The variants, by the nature of things, could not help but be unforesighted; though some designers might view drag as theoretically controlling, no one could foresee for sure how practical requirements would work out. As speeds went up and reduction in drag became overriding, the design community in the end, through practical ingenuity and cumulative decision, selected retraction for the long-term generic solution. Though the social desire for speed shaped the direction for this change, a technical imperative can now be seen to have shaped its form. In solving the generic problem, Northrop's trouser gear, far from an anomaly, was an integral part of the learning process. Variation-selection in more or less such pattern, I suggest, supplies the methodology for long-term solution of general engineering problems. Where an overriding technical imperative does not exist (which may constitute even the majority of cases), social shaping may well be crucial, but still within a variation-selection framework when the problem is new to engineering experience.[58]

Pinch and Bijker, in their social-constructivist discussion of the bicycle, point to the importance of including all relevant variants in analyzing a variation-selection episode; the quotations cited earlier from Williams and Edge imply the same. To find *all,* one must look, not only for the successes and failures, but also for the also-rans. These last, which were brought home to me initially by examination of the Davis wing,[59] are the variants that work well enough for a while but, for one reason or another, disappear from the scene. Northrop's trouser gear was of this sort. All play a role in the technological learning process.

This implication of the variation-selection model may have value for historians of technology. A pitfall for all historians, of course, is that we know the outcome of the events we study. This knowledge cannot help but color our selection and interpretation of those events. Historians of technology need to be especially alert to this pitfall since technological problems, to a greater degree than social ones, often find solutions that a majority of people regard as in some sense "correct." As in the usual view of the retractable landing gear, the

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[58] The narrative of this article may appear to some as simply another in the many historical examples of a new technology (retractable gear) displacing an old one (fixed gear). The analysis should then be seen as a not-so-customary attempt to sort out what goes on epistemologically—or at least went on in this case—in the complex learning period when the old technology competes side by side with the new.

[59] Vincenti, *What Engineers Know* (n. 2 above), pp. 16–50, esp. p. 49.

temptation exists to see these as foresightedly preordained solutions toward which everyone was working, perhaps even knowingly, at the time. It is all too easy to overlook the variants that accompanied the long-term preferred solution and thus distort and misread the learning process.[60] The variation-selection model can be useful—as it was for me with regard to the Northrop "anomaly"—by inspiring search for the variants and emphasizing the role of unforesightedness. If this tale has a moral, perhaps it is this: cherchez la variation.

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[60] These thoughts also relate to Herbert Butterfield's concept of the "Whig interpretation of history" and the discussion it has engendered. See H. Butterfield, *The Whig Interpretation of History* (London, 1931); and, e.g., E. H. Carr, *What Is History?* (New York, 1961), pp. 25, 50–51; and D. H. Fischer, *Historians' Fallacies* (New York, 1970), p. 139.