

**Why evolution is a theory about stability: constraint, causation, and ecology in
technological change**

Edward W. Constant II

Department of History

Carnegie-Mellon University

Abstract: Evolution, like history, is ordinarily thought to be about change in time. Yet a surprising variety of “evolutionary” models across multiple domains are at least as much about stability, or at least secular stasis, as they are about change. Our narrative forms, as well as our likely evolutionarily produced disposition to attend to difference rather than to stasis, reflexively bias our perception of evolution itself. A sample technological narrative, and a constructed anti-narrative, together with an examination of the structure of engineering design processes (derived from Walter Vincenti), and some insights from actor-network theory, point to the complex causal interconnections between stable and innovative elements in technological change.

Recall the problem Darwin sought to solve: The explanandum of his theory was living species' remarkable diversity and seemingly near-perfect, indeed "intelligent," adaptation to each other and to their environment. Before Darwin, the consensus explanans for this extraordinary triumph of design was divine creation. Darwin studied history to escape god: He looked to evolutionary change in geological time to account for the persistent stability and diversity he saw around him in real time. Reflexively, evolutionary psychologists tell us that there are good reasons why we attend selectively to change rather than to stasis: Attention to change, difference, or motion is more likely to put food on our table, or mates in our bed, or to signal us hazard of our becoming some other species', or some conspecific's, repast. But an essential element in all change nevertheless remains stasis. As Donald T. Campbell so aptly phrased it,

Our only hope as competent knowers is that we be the heirs of a substantial set of well-winnowed presuppositions. From the hypothetical ontology of modern physics and biology it seems plausible that this might be so, that we might have come from a highly selected ancestry of organisms presumptively living by unproven recipes, presumptively knowing in modes that later turned out to have worked somewhat better than other modes, while the world was the way it was, and still may be.¹

Putative “evolutionary” theories across a surprising variety of domains are also theories about stability (Table 1). Indeed, the notion of evolution itself only makes sense against a background of stable elements. Evolutionary biology is increasingly dominated by what is coming to be known as “evo-devo,” the combination of classical selectionist evolutionary theory (grounded in paleontology and cladistics), genetics, biochemistry, and contingent phenotypic development. In this new synthesis, some paleontologists emphasize the extraordinary morphological stability of phyla and families through long epochs of geological time, while molecular biologists note the commonality of protein sequences and structures, macromolecular “messengers,” and cellular receptor sites across large sets of phyla and species, both quick and dead. Nature, it seems, prefers to invent once, use many.

Students of science likewise stress the stable background against which, indeed from which, scientific progress develops. Imre Lakatos argued that science develops by rigorous pursuit of progressive research programmes which comprise “core hypotheses,” unchanging theoretical commitments and models, which scientists are extremely reluctant to give up. This core is surrounded by a “protective belt” of auxiliary hypotheses which are largely expendable, or easily modified. Progress comes from robust extension of the programme’s core.

Table 1: Elements of stability in evolutionary theories

Model	<i>Stable elements</i>	<i>Dynamic mechanism</i>
evo-devo	amino acids, protein sequences, DNA structure, morphological forms	mutation, developmental contingencies
Rosenberg and Mowery	embodied capital technological convergence incremental change (especially process) complementarities	invention innovation R&D
Nelson and Winter	firm (unit of selection) skill/routines organizational capabilities (satisficing) decision rules	problem solving random events (endogenous or exogenous)
Lakatos	core hypotheses of research programme, “unproblematic” background knowledge	“protective belt” of auxiliary hypotheses; extension
Kuhn	paradigms normal science	persistent anomalies, incommensurable “gestalt” switch
Vincenti	operational principle normal configuration technical constraint	radical innovation
Hughes	system technological momentum	reverse salients critical problems (innovation)

Chandler	organizational capabilities; tripartite investment in technology, markets, and management; organizational culture	markets (environment) technology economies of scale and scope
Campbell	well-winnowed presuppositions	random variation selective retention
Mokyr	selection environment (vehicles, interactors – artifact, firm, market)	technique (routine, instructions)
Bijker	closure obduracy technological frame semiotics of power	social construction low inclusiveness

Thomas Kuhn, of course, juxtaposed paradigmatic normal science, which comprises the vast bulk of scientific endeavour, with rare and extraordinary “gestalt switches,” or revolutions, which generate new beliefs incommensurable with prior beliefs. Donald Campbell, in his much broader evolutionary epistemology, attributed *all* increases in the “fit between noumena and phenomena” to a nested hierarchy of random variation-selective retention processes which yield “well-winnowed presuppositions,” or stable knowledge. Thus the amoeba “knows” when to swim up a nutrient gradient, and down a toxic gradient, in the same sense that a scientist knows to use the immense

corpus of “unproblematic background knowledge” in his exploration of the unknown.

Concepts of technological and economic evolution deploy similar elements of stability and change. In the design process, Walter Vincenti juxtaposes stable operating principles, normal configurations, and standard technological constraints, to rare, radical innovations. Thomas P. Hughes sees the primary mover of continuing technological progress as Newtonian “momentum,” which pushes a technological system along its pre-determined trajectory, unless and until deflected by external social or political forces, or stalled by a “reverse salient,” which induces more or less radical innovation. Alfred Chandler argues that tripartite investment in *industry specific* technology, management, and markets, which constitute the core organizational competencies of the firm, assure long-run persistence, profits, and power.²

“Gales of creative destruction” notwithstanding, economists such as Nathan Rosenberg and David Mowery stress the economic primacy of embodied capital, technological convergence, and incremental change. Paul David highlights the importance of path dependency and developmental constraints, as in the famous case of the QWERTY keyboard. Joel Mokyr sees “technique,” by which he means a routine or instructions to accomplish some task, as the unit of

evolution and selection. But this technique implicitly is set within a selection environment – vehicles or interactors, which can be artifacts, firms, or markets – that are not themselves fully malleable. Nelson and Winter themselves locate economic evolution within and among relatively stable firms, the units of selection in their theory, which deploy obdurate skills and routines, organizational capabilities, and satisficing decision rules. Novelty arises, subject to selection, from the problem-solving action of the firm, as well as “random events,” which can be endogenous or exogenous. Even social constructivists, such as Wiebe Bijker, who ordinarily eschew both economic superiority and technical efficacy as selection criteria, talk about technological frames, closure, obduracy, and a stable sociotechnical “semiotics of power.”

Despite the obvious importance and preeminence of stable elements in all of these evolutionary theories, the narratives we tell still stress change and discontinuity. Let me offer one such conventional narrative, then provide an anti-narrative to try to reconstruct it in a way that takes greater account of the stable structural elements in technological evolution.

THE LOCKHEED F-104 STARFIGHTER: THE HISTORICAL NARRATIVE

By any account, and there are many – over 3000 web sites are devoted to the airplane as this is written – the Lockheed F-104 Starfighter is extraordinary. It was originally designed nearly half a century ago, in 1952, at the apogee of Lockheed, and American, piston-engined airliner development: Lockheed's Constellations remain the paragon of piston-engined civilian airplanes (<http://home.wxs.nl/~raaph019/constellations.html>). The F-104 was the product of Lockheed Aircraft's resident genius, Clarence L. "Kelly" Johnson, who had designed the pre-war P-38 Lightning, as well as the P-80 Shooting Star, the United States' first operational turbojet aircraft, and the first product of Lockheed's famed "Skunk Works."³ (Johnson later would design the U-2, and the Mach 3 SR-71 Blackbird reconnaissance aircraft., and the Skunk Works would produce the F-117 Nighthawk Stealth fighter.)

Johnson had gone to Korea and talked with American fighter pilots to find out what they wanted in a successor to then first-line P-80s and F-86 Sabre Jets. Perhaps reflecting a romantic nostalgia for their World War II glory days more than the realities of aerial combat in the jet age, the pilots expressed a distinct preference for a very fast, fully supersonic, fast-climbing daylight air superiority fighter. They discounted both radar sights and guided missile armament,

preferring instead visual contact and gun armament, although the phenomenal closing speeds of supersonic air combat would require extraordinarily rapid-firing guns,⁴ a requirement ultimately fulfilled by the revolutionary General Electric “Vulcan” rotary six-barreled 20 mm cannon.

Johnson’s answer to the pilots’ prayers, the F-104 (Figure 1, or <http://www.danshistory.com/f104.html>, and <http://home.pi.net/~harrylui/home.html>; for Royal Danish Air Force F-104Gs, <http://members.home.nl/h.luijkx/norwdenm/>) weighed half as much as any other century series (F-100 plus) US fighter, and was the first production airplane in the world capable of sustained Mach 2 supersonic flight. It had a maximum speed of Mach 2.2, or 1450 m.p.h. at 36,000 feet (F-104C and F104G versions), a service ceiling of 60,000 feet, and an initial climb rate in excess of 50,000 feet per minute (F-104G).⁵ During the late 1950s and early 1960s, variants of the F-104 set a whole series of international performance records: Maximum level speed, 1404.09 m.p.h. (F-104A, 1958), altitude (“zoom climb”) 91,249 feet (F104A, 1958),⁶ and time to climb. In 1959, an F104C reached an altitude of 103,389 feet, making it the first airplane in history to take off under its own power and exceed 30,000 meters and 100,000 feet. In 1964, an F-104G was used to set women’s world speed records: 1429.3 m.p.h. absolute, 1303.18 m.p.h. over a 100 km closed course, and 1127.4 m.p.h. over a 500 km close course.

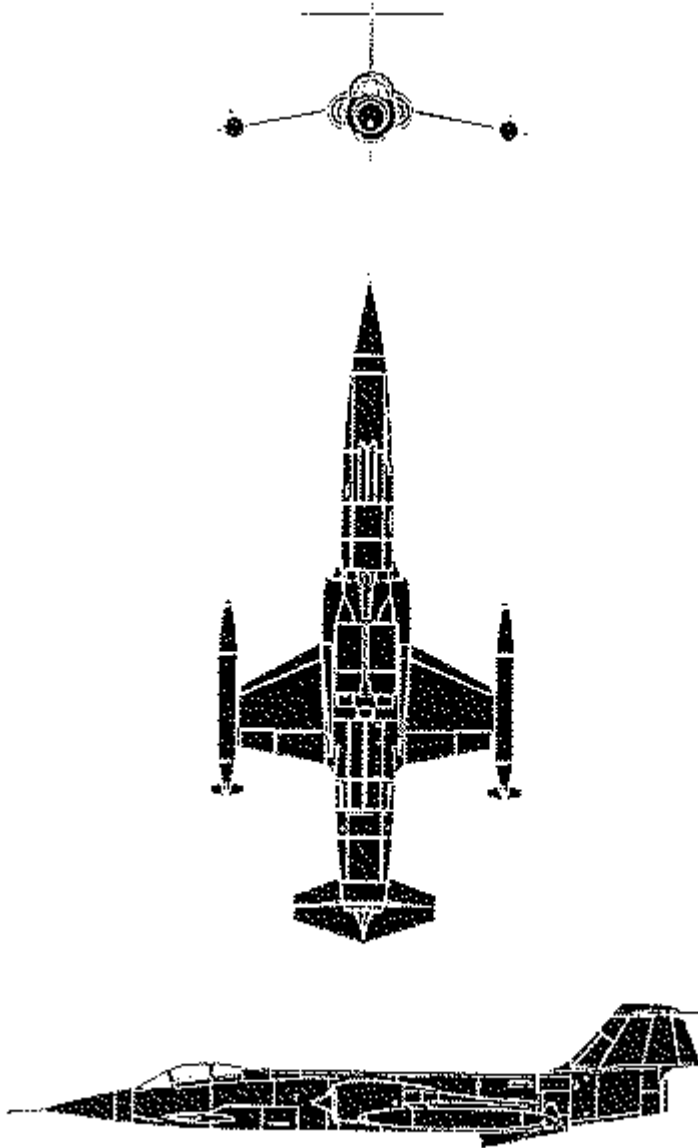


Figure 1: Lockheed F-104G Starfighter

Span 21 ft. 11 in.; length 54 ft. 9 in.; height 13 ft. 6 in.; wing area 179 sq. ft.
Max. weight 28,779 pounds

The design of the F-104 was as extraordinary as its performance: it was unlike any other production aircraft. The F-104's most distinctive feature was its wing: Without tip tanks, total wing span was only 21 feet 11 inches (compared to 35 feet 10 inches for a Cessna 182). Each F-104 wing individually spanned only 7 feet, 7 inches, for a total wing area of 196 square feet. At a maximum take-off weight of 28,779 pounds, an F-104G had a wing loading of 148 pounds per square foot – compared to 103 pounds per square foot for an F-4B Phantom II,⁷ 136.3 pounds per square foot for a Boeing 747B, 100 pounds per square foot for a Concorde supersonic transport, or 67 pounds per square foot for a Lear 35.⁸

The very small wing and very high wing-loading of the F-104 reflected Johnson's bold choice among available supersonic wing planforms. At the time the F-104 was designed, production trans-sonic aircraft used either sharply swept wings with separate, also swept, horizontal tail surfaces, as on the North American F-100 Super Sabre (Figure 2, or http://cybermodeler.com/f-100/images/century_series.jpg), or relatively large-area, very sharply swept delta wings, which combined wing and horizontal tail surfaces, as on the Dassault Mirage III (Figure 3, or <http://www.geocities.com/Pentagon/Base/3303/>) or Convair F-106 Delta Dart (Figure 4, or http://userpages.aug.com/~dlhst/f106_delta_dart_pictures.htm).⁹

The alternative to these types was a relatively straight, but extremely thin and

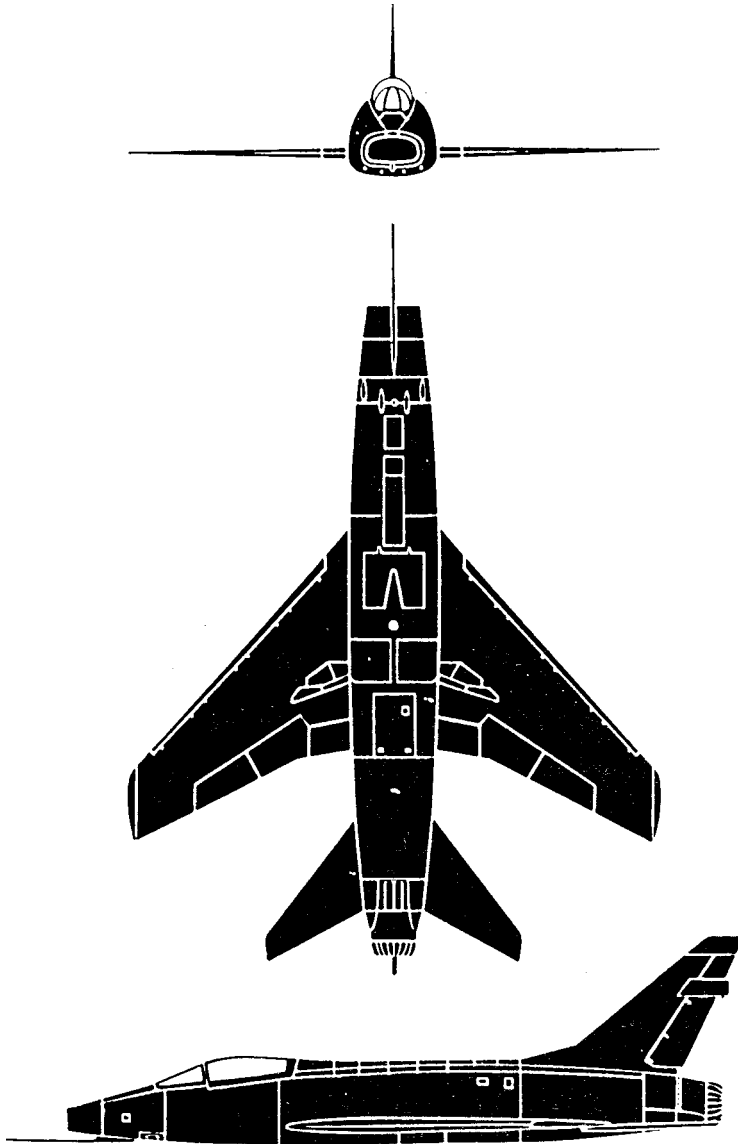


Figure 2: North American F-100D Super Sabre

Span 38 ft. 9.5 in.; length 54 ft. 3 in. (including pitot boom); height 16 ft. 3 in.;
wing area 385 sq. ft.; Max. weight 38,500 pounds

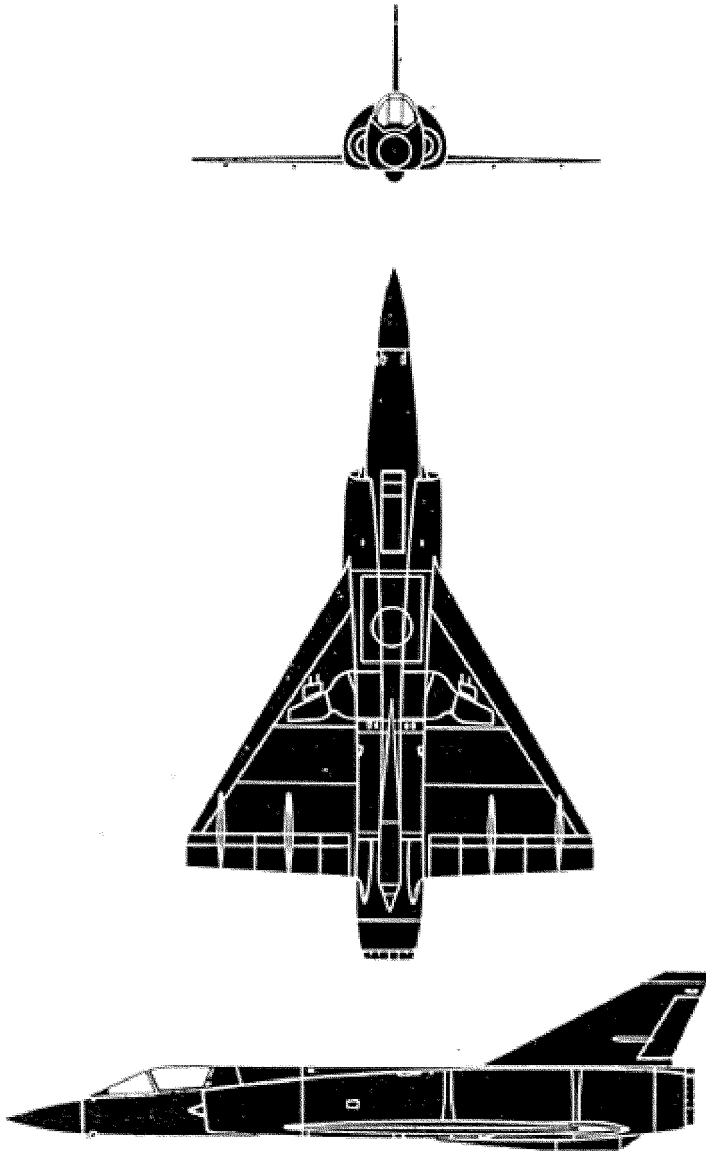


Figure 3: Dassault Mirage III C

Span 26 ft. 9 in.; length 43 ft. 10 in.; height 14 ft.; wing area 374 sq. ft.;
Max. weight 26,000 pounds

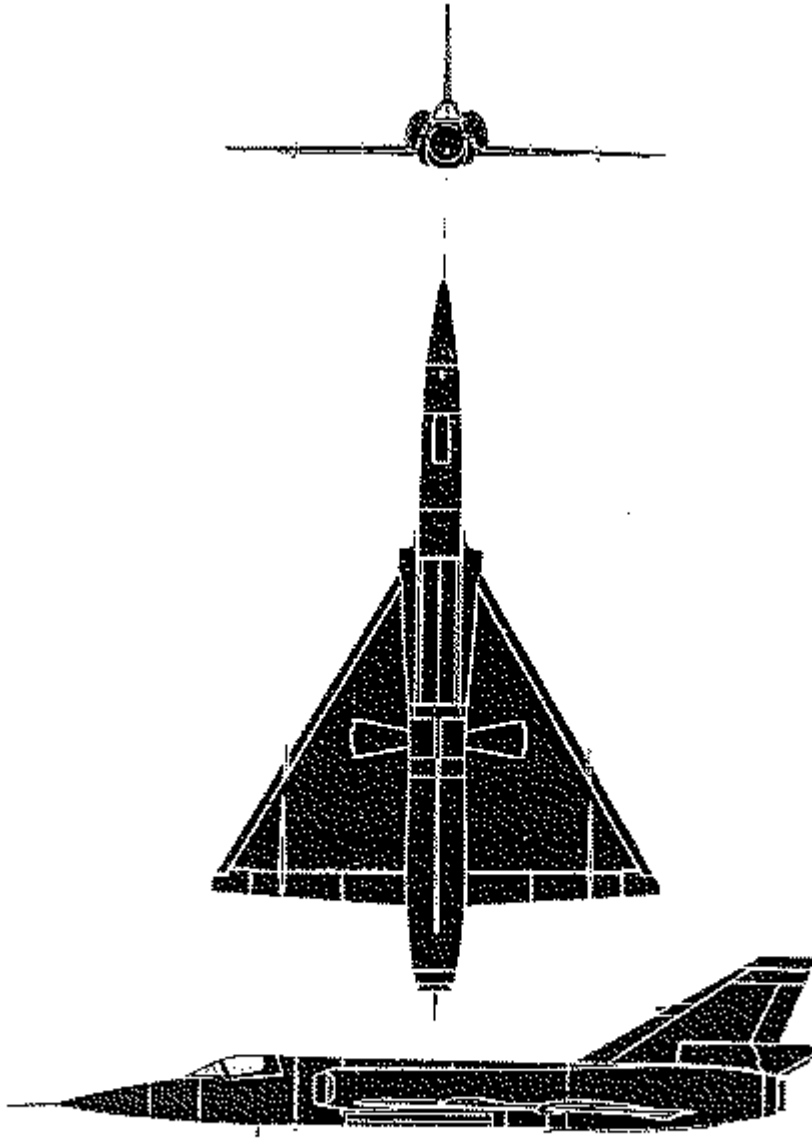


Figure 4: Convair F-106 Delta Dart

Span 38 feet 1.5 in.; length (including nose probe) 70 feet 9 in.; height 20 ft. 3.5 in.
Wing area 661.5 sq. ft.; Normal loaded weight, 35,000 pounds

small wing, a type first seen on the experimental Douglas X-3, which never attained its designed performance because of engine deficiencies. Highly swept wings require relatively long spans and thick cords (“width” from leading to trailing edge), and thus have to be relatively thick. Delta wings present more complex trade-offs:

Every square foot of delta wing has less drag in a certain mach number region ... than a corresponding square foot of straight wing. Every square foot of straight wing, however, lifts roughly twice that of a delta. By the time there is enough delta wing area for a given load, total drag is considerably higher than a straight wing¹⁰

Furthermore, *ceteris paribus*, although a delta-winged airplane could accelerate through the “sound barrier” (Mach 1) faster than a straight-winged airplane, the straight-winged airplane enjoyed significant acceleration advantages in the supersonic regime. Since the F-104 was designed to operate continuously at supersonic speeds, a very thin, relatively straight wing promised substantial advantages.

Choice of the straight wing, however, posed severe structural challenges. To achieve acceptable supersonic performance, the wing had to be extremely thin (tapering from 4.2 inches deep at the fuselage to 1.96 inches at the tip), with very sharp leading and trailing edges (the leading edge had a nose radius of only 0.016 inches, or 0.041 cm).¹¹ But the wing also had to be extremely rigid to avoid aileron-induced deflection and consequent control reversal. Lockheed's solution was to use a spar and transverse core machined from a single aluminum slab covered with single-piece, relatively thick (tapering from one-half inch to one-quarter inch) upper and lower aluminum skins. The skin was shaped in a compression die, which produced both a very level wing surface and precisely formed rivet holes, which together permitted the extraordinarily smooth surface necessary for efficient supersonic flight. Both leading and trailing edges were reported to be "sharp enough to slice lunch meat."

The F-104's unique wing design necessitated further design adaptations. To enhance maneuverability and reduce landing speed, the entire leading edge was a separate structure which could be electrically "drooped" to increase low-speed or high-angle-of-attack lift. The entire trailing edge was hinged, the outer panels being the ailerons, the inner panels flaps. From the F-104A model on, the flaps were "blown" – high-pressure air bled from the engine compressor was fed through nozzles forward of the flaps to prevent boundary layer separation and

maintain lift.¹² Even with such aids, F-104 take-off and landing speeds approached 200 knots (230 m.p.h.). The wide flight envelope of the F-104 – from 200 to more than 1300 knots – dictated choice of a high “T” tail to maintain pitch stability, while supersonic speeds entailed a horizontal tail planform, and thinness, similar to the wing’s. In turn, the greater roll moment of the high-tail dictated the F-104 wing’s unique 10 degree anhedral. Moreover, engineers initially believed the high tail to pose a hazard to a pilot ejecting upward from the cockpit, so initial versions of the F-104 were fitted with a unique, Lockheed designed, downward ejecting seat – not advisable to use on or near the ground. Later, when adapted for the ground attack role, European F-104Gs were fitted with conventional upward ejecting seats of either Lockheed or Martin-Baker design. The thinness of the wing left no room for the retracted landing gear or its mechanism, so the main gear was designed to retract obliquely forward into, and fit flush within, the fuselage.

The wide Mach range for which the F-104 was intended also presented unique challenges for turbojet engine design. The F-104 used the General Electric (GE) J79, the first US high-compression, variable stator turbojet, and the first US Mach 2 production engine. The wide speed range of Mach 2 aircraft entailed very large differences in both volume and velocity of intake air, and required rapid acceleration, without compressor stall (which would extinguish the engine

– cause it to “flame out”). The J79 used variable-incidence inlet guide vanes as well as variable-incidence stator blades on the first six of its seventeen compressor stages, all activated by mechanical linkages operated hydraulically by fuel pressure. The J79 also used a variable nozzle afterburner, fixed power initially, fully variable in later versions. In addition to the F-104, the J79 engine appeared in a variety of other Mach 2 airplanes: the USAF Convair B-58 Hustler and USN North American A-5A Vigilante bombers, and both Air Force and Navy McDonnell F-4 Phantom II multi-role aircraft. A civilian version of the J79, without afterburning, the GE CJ-805, powered the Convair 880, whose maximum cruise speed of 535 knots makes it still the world’s fastest sub-sonic airliner.¹³

The Korean War-era daylight air superiority role for which the F-104 was initially designed was largely superfluous to the USAF by the time the F-104’s development was completed in 1957. F-104As were briefly issued to USAF Air Defense Command (later the North American Air Defense Command, or NORAD) squadrons, pending delivery of the development-delayed Convair F-106 Delta Dart, but the F-104As were withdrawn and assigned to Air National Guard units by 1960. Some F-104Cs and Ds – ground support versions of the F-104 – were deployed by USAF Tactical Air Command, but again were soon replaced by heavier airplanes with greater range and payload (principally Republic F-105 Thunderchiefs and F-4 Phantoms).

Ironically, the F-104 is perhaps best remembered in its F-104G multi-role version, in which guise it was supposed to meet NATO requirements for a day-light air superiority fighter, an all-weather interceptor, and a ground attack aircraft. To fulfill these diverse missions, the F-104G had a strengthened structure, larger tail, and substantially up-graded avionics and radar. Starfighter service in NATO and other western air forces proved controversial in more ways than one. First, the F-104 was an extremely demanding airplane to fly – it was particularly challenging in take-off and landing – and it suffered what were perceived to be inordinately high accident rates. In fact, in USAF service, it did experience total accident rates, aircraft loss rates, and fatal accident rates higher than any other supersonic fighter aircraft except the North American F-100 Super Sabre. Poor weather in northern Europe only exacerbated the problem. Between 1961, when the *Luftwaffe* operationally deployed its first F-104Gs, and 1989, when the last airplanes were withdrawn from regular squadron service, the *Luftwaffe* (West German air force) and *Marineflieger* (West German naval air force) had written off due to accidents 292 of their 916 F-104s. At one point early in the F-104's deployment, before its pilots were receiving adequate flight time, or the airplanes adequate maintenance, the West Germans were losing an airplane a week.¹⁴ The high loss rates, combined with questions about the original decision to buy the F-104, reverberated through West German politics for nearly ten

years, and, with the eruption of a bribery scandal in 1975 involving Lockheed and foreign government officials, the F-104's reputation was forever tarnished.

A total of 2578 F-104s of all versions were produced world-wide. Lockheed built 741, plus another 48 assembled abroad. As noted below, the remainder were built by aircraft firms in a number of allied countries. Of the total produced, the USAF operated only 277, versions A through D. The rest served at one time or another in thirteen other, mostly allied, air forces (Table 2).

Table 2: F-104 Operators

Air Force	Number
Belgium	113
Canada	239
Denmark	51
Germany	916
Greece	159
Italy	360
Japan	230
Jordan	36
Netherlands	139
Norway	43
Pakistan	12
Spain	21
Taiwan	281
Turkey	379
USAF	277
NASA (civilian)	14
Total	3270

Note: Total number of aircraft operated is greater than the number produced because aircraft are transferred among nations.

The narrative you've just read is pretty much what you'd expect: It tells you everything that's unique, different, distinctive, scandalous, or "interesting" about the F-104. It even has all the cutely fearsome little "names" – Starfighter, Vigilante, Thunderchief – so beloved of air force PR flaks and airplane trivia buffs. It's also broadly typical of the sort of narratives about technological change historians of technology, economic historians, students of R&D or R&D management or policy, or even economists construct. It's likely pretty much what you'd find on any of the 3000 plus web sites devoted to the F-104 which bother to have an "historical" component. What this standard historical narrative doesn't tell you is everything that's mundane, commonplace, conventional, derivative, standard practice, or widely shared about the F-104, which *is* pretty much everything.

Start with the airplane: However innovative in some respects, and despite being optimized for supersonic flight, the F-104 still has an utterly conventional *operational principle*, as Walter Vincenti, following Michael Polyani, calls it: "For the aeroplane ... the operational principle, as first set forth by Sir George Cayley in 1809, prescribes that the upward force required to counteract the vehicle's weight be generated by propelling a fixed surface forward through the resisting air."¹⁶ Similarly, also following Vincenti and Polyani, the F-104 exhibits the

*normal configuration*¹⁷: the nose is in front, the tail is on the back, the wings are in the middle, the airplane is bilaterally symmetrical, and the cockpit is on top. The same could be said of the GE J-79 turbojet: However innovative and difficult to develop its variable compressor stators may have been, its operational principle and configuration were, by 1950, utterly conventional. Ditto the compressor and turbine blade profiles, compressor and turbine disks, means of attaching blades to disks, fabrication techniques, and so on. The fuselage of the airplane was a conventional stressed-skin monocoque structure, even if it did use some stainless steel and titanium.

Although the extremely thin wings and tail surfaces of the F-104 presented unique packaging challenges for aileron, flap, and leading edge activation, the systems designed for those functions followed conventional lines. The wings also were too thin to accommodate the retracted main landing gear and its mechanism, so the main gear retracted obliquely into the fuselage. While this arrangement was unusual, and the oblique axis of the main gear mounting hinges unique (to permit the retracted gear to lay flush within the fuselage), the gear mechanism itself used a light-weight Dowty patent “liquid-spring shock absorber.”¹⁸ Indeed, if one were of a mind to, one could take a F-104 parts list and go through the airplane component by component, right down to the

fasteners, o-rings, rivets, and hydraulic fluid, and show just how much traditional, common-place technology it comprised.

Conceptually, Walter Vincenti offers perhaps the best guide to understanding design hierarchy and constraint, and, by extension, its internal causal structure.¹⁹ Vincenti locates any component or facet of design for a complex system on a curved surface described in a three-dimensional space defined by three axes: radical to normal type of design, upper to lower level in the system hierarchy, and low to high degree of technical constraint (Figure 5):

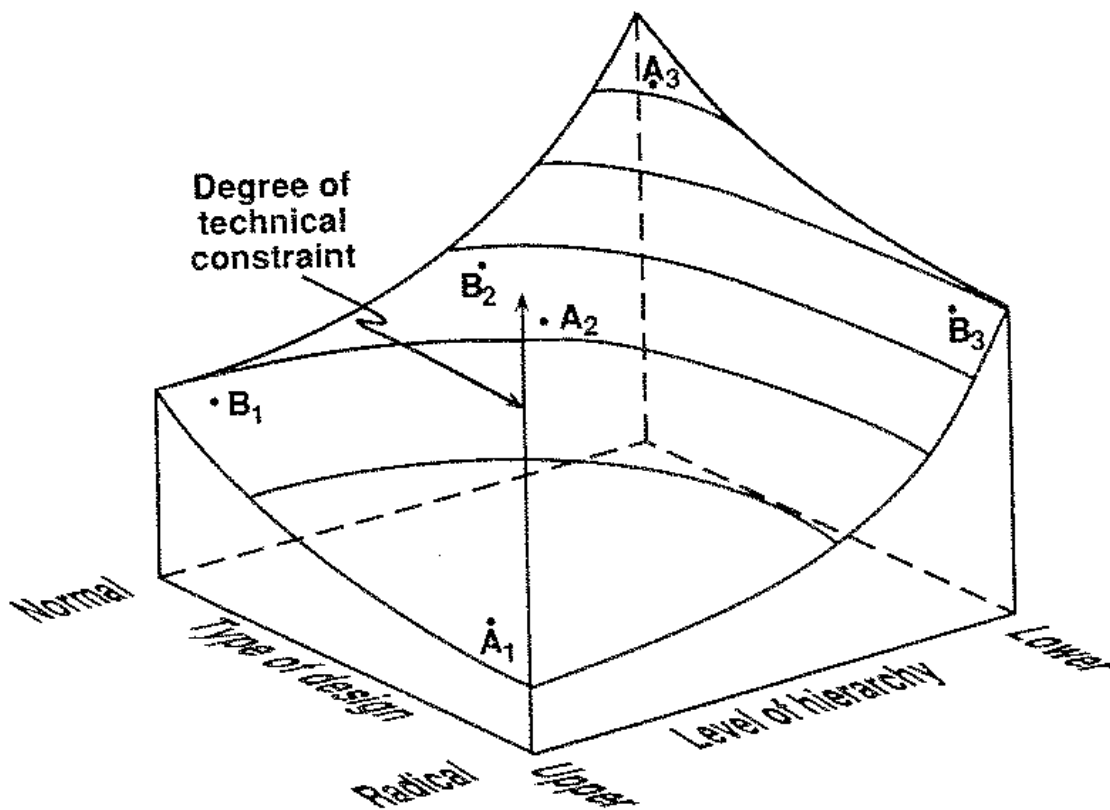


Figure 5: Technical Constraint as a Function of Design and Level of Hierarchy (Vincenti)

To use the diagram, it must be understood that design at different hierarchical levels within a given systemic device does not all take place at the same location between radical and normal. For example, a radically new type of aircraft with a conceptual design situated at A_1 on the diagram might incorporate a more or less conventional landing gear represented at A_2 , made up in turn of

completely conventional subcomponents located at A_3 . Or a conventional overall concept at B_1 could have an equally conventional landing gear at B_2 and (should some sub-component designer have a bright idea) a radically new type of landing-gear shock absorber at B_3 .²⁰

Vincenti also emphasizes that design “takes place iteratively and interactively throughout the hierarchy.”²¹ He further notes, “To circumvent technical constraints is often exceedingly difficult, the more so the greater the number and rigidity of the constraints. To the extent that the constraints involve physical laws, it may even be impossible.”²² Well-winnowed “physical laws,” or strongly corroborated beliefs, although not easily represented in Vincenti’s graph, not only constrain design, but also proactively direct vicarious exploration of and vicarious selection within alternative design spaces, and give to them their much of their “rational” character.

Even though Vincenti might not frame the issue quite this way, in effect, given the structure of a system, different “points” on Vincenti’s diagram can be connected *causally*. Choice of wing design will constrain landing gear configuration (as in the F-104); landing gear configuration (and space) will constrain shock absorber choice. Conversely, limitations on tyre pressure,

temperature (a function of landing and take-off speed), and size and weight, will constrain landing gear size and weight. Imagine Vincenti's diagram filled in with all the components (points) in the system, with causal arrows connecting all the relevant points: What emerges is a thick network or thicket of causal interrelations. Evolutionists, of course, will recognize in this thicket the familiar structure of downward causation, upward causation, and developmental constraint.

THE ECOLOGICAL WEB AND ITS STABILIZATION

An alternative way to get at the preponderance of stable elements in even highly innovative systems is to look at who or what builds them. The F-104 is unusual in that Lockheed actually built only slightly more than a quarter of all the airplanes manufactured. The rest were built in seven different countries. Although Messerschmitt was Lockheed's lead European partner, the European airplanes actually were built by European consortia comprising four major nodes: ARGE Süd (Germany), ARGE Nord (the Netherlands, Germany, Belgium), the "West Group" (Belgium and Germany) and the "Italian group" (Italy). GE J-79 engines for these airplanes were built under license by BMW in Koblenz, West Germany, with some components supplied by FN (*Fabrique Nationale*) in Brussels, Belgium; others were coproduced by MAN in Germany

and Fiat in Italy. The European consortium was coordinated by “the NATO Starfighter Management office (NASMO)” also in Koblenz.²³ Figures 6 a-d depict the European consortia and their constituent firms, together with some indication of what sub-systems or components each manufactured.²⁴ Total European employment in the F-104 programme peaked at about 100,000. In addition, F-104 variants were built by Canadair in Canada (CF-104), with GE J-79 engines license built by Orenda, and by Mitsubishi in Japan (F-104J) with engines license built by Ishikawajima-Harima. Table 3 summarizes F-104 production. That so many manufacturers and sub-contractors world-wide participated in producing the F-104 and its sub-systems strongly implies that the airplane and its components were well within the technological capabilities of any modern, reasonably competent aerospace firm.

Figure 6a: NATO F-104G Consortia



Figure 4b:**ARGE (Arbeitsgemeinschaft) Süd**
("Work Group South," Munich)
210 + 50 F-104Gs

Messerschmitt, Augsburg

- flight testing
- final assembly
- painting
- assembly of pilot seat, fuselage, wing and tail
- flaps, ailerons, wing leading edge
- power plant installation

Heinkel, Speyer

- main landing gear
- drop tanks (fuel)
- main landing gear door
- dive brakes
- wings
- fins
- rudder
- horizontal stabilizer

Dornier, Munich

- mid-fuselage panels
- upper fuselage panels
- nose landing gear

Siebel, Donauwörth

- canopy
- electronics bay hatch cover
- nose landing gear doors
- fuel tank cover and hydraulic access door
- fuselage nose
- air intakes
- rear fuselage

Messerschmitt-Bolkow-Blohm (MBB)
assembly of a further 50 F-104Gs

Figure 4c:**ARGE (Arbeitsgemeinschaft) Nord**

("Work Group North," Schiphol, Amsterdam)
350 F-104Gs

Fokker, Amsterdam

- flight testing
- final assembly
- painting
- assembly of pilot seat, fuselage, wing and tail
- power plant installation
- electronics bay hatch cover
- escape hatch
- after fuselage
- flaps, ailerons, wing leading edge
- rudder
- horizontal stabilizer
- drop tanks

Aviolanda, Dordrecht (Netherlands)

- fuselage nose
- radome
- fuselage
- canopy
- nose and main landing gear
- fuel tank covers

Hamburger Flugzeugbau (HFB), Hamburg

- windshields
- fuselage panels

Weserflugzeugbau, Bremen

- mid-fuselage panels

Focke-Wulf, Bremen

- hydraulic access doors
- air intakes, scoops

Figure 4d:**West Group**

(Gasselies, Belgium)

187 F-104Gs

Avions Fairey S. A.

Société Anonyme de Constructions Aéronautiques (SABCA)

Components from Siebel, Heinkel, and Dornier

Italian Group

(Turin-Caselle)

124 F-104Gs, 205 F-104Ss

Fiat

Aerter

Macchi

SIAl-Marchetti

Piaggio

SACA

License-built J79 engines:

BMW, Koblenz

Fabrique Nationale, Brussels

MAN, Augsburg

Fiat, Turin

Table 3: F-104 Production (Assembly)

Lockheed (USA)	741 plus 48 = 789
Canadair (Canada)	340
Fiat (Italy)	444
Fokker (Netherlands)	350
MBB (Germany)	50
Messerschmitt (Germany)	210
SABCA (Belgium)	188
Mitsubishi (Japan)	207
Total	2578

Note: Production totals include some follow-on airplanes

But how the F-104 was produced suggests a lot more than just the normalcy and stability of its *internal* components. Look again at Figures 6 a-d, but now from the perspective of an actor-network theorist.²⁵ Think of the European F-104 consortia as a network of human and non-human actants: of firms, managing directors, labour unions, stamping machines, cutting tools, truck drivers, transmissions, hydraulic fluid, all knitted together by the artifact F-104G into a stable and obdurate network of alliances. Now set this actor network within an even larger network of actants: the NATO air staff, the West German Luftwaffe, the Belgian or Danish air forces, bankers and finance ministers, aerodromes and radar sets, the US's Military Assistance Program (MAP), and nuclear weapons (some Luftwaffe F-104G ground attack aircraft were nuclear-capable). In a very real sense, NATO produced the F-104G, but the artifact F-104G also produced and stabilized the obdurate set of relations known as NATO.²⁶

Even if one were less venturesome than a fully orthodox actor network theorist, and were queasy about attributing agency to non-human actants, alternative theoretical approaches suggest much the same pattern. In the ecology of the trans-national consortia, the F-104 becomes what Susan Leigh Star calls a "boundary object," which circulates among diverse social groups which must cooperate in some task: the boundary object is "both adaptable to different

viewpoints and robust enough to maintain identity across them.”²⁷ Joan Fujimura broadens the concept of boundary objects to “standardized packages.”²⁸ A “standardized package,” according to Fujimura, “facilitates both collective work by members of different social worlds *and* fact stabilization.” It

... differs from a boundary object in that it defines a conceptual and technical work space It is a *gray box* which combines several boundary objects ... with standardized methods ... in ways which further restrict and define each object.

Such a standardized package “serves therefore as an *interface* between multiple social worlds.”²⁹

On either the full actor-network or the boundary object account, what matters is that the F-104 stabilized and rendered obdurate not only the social, economic, and political interests, but also the concrete technological means and practices, of all those associated in the F-104 programme.

EVOLUTION AS SECULAR STASIS

As noted at the start, virtually all “evolutionary” theories, from biology to economics and back again, have at their core stable elements. Nevertheless, the way we construct evolutionary narratives, especially those about technology, typically effaces all that is stable, unchanging, or ordinary, and emphasizes almost exclusively that which is radical, unusual, innovative, or unique. This attentive bias itself likely reflects our own evolutionary history: stasis is unrewarding and dull. We scan our environment for anomaly or movement or difference or change or danger or opportunity, and when we don’t see it, whether on the dials of a nuclear power plant, or on a long, straight concrete slab of highway,³⁰ in a hunting blind, or in a fern bar, we do the sensible thing and go to sleep.

The F-104’s anti-narrative tries to retrieve some of what is lost in normal historical narrative. There stable elements of practice and technology are foregrounded.³¹ The stabilization of the artifact F-104 occurs at least three levels: at an internal or micro level, at a “meso” level of production technologies, and at a macro or ecological level. Internally, most components and subsystems are not unique to the F-104, and, following and extending Vincenti, generate a complex, mutually determining set of causal connections which powerfully constrain the overall character of the airplane’s design. Similarly, the production technologies, processes, and practices from which those components and sub-systems derive

provides another set of overlaying constraints on what is possible, feasible, or economical. Micro level constraints are analogous to “internal” developmental (nee embryological) constraints in biological systems, while the meso level production constraints might be thought of as analogous to environmental circumstances which trigger, shape, or restrain gene expression, or select developmental pathways.³²

The obdurate network of stable alliances which the F-104 produced and sustained comprised its macro environment, or ecology. The artifact F-104 produced, and was produced by and embedded within, a thick ecological web, without which it could not have existed, and which would not have existed without it. Once the F-104 was “on the ground” (if you’ll excuse the expression), to the extent its network was effective (if not efficient) in exploiting environmental resources, and incorporating them into the network itself (think about defense budgets), “it” (the artifact F-104 and its network) established powerful barriers to entry for any similar species of aircraft.

None of this, of course is really news to students of technological change. The stabilization of obdurate networks of human and non-human actants has many faces and many names: complementarities, economies of scale and scope, installed base, first mover advantages, network advantages, backward

compatibility and legacy systems, embodied capital, and the historian's golden oldie, "vested interests." But these circumstances are often treated as contingent consequences of specific historical instances, not as an essential feature of all technological evolution.

Secular stasis, then, *is* an essential feature of technological evolution, as it is in the punctuated equilibria version of biological evolution. But secular stasis is not the same thing as permanence. Look one more time at the F-104's ecological web (Figure 6 a). Now add the French, who never flew or produced F-104Gs, preferring instead their own Dassault Mirages and F1s. Presto, change-o, behold Airbus Industries. I'd suspect that the organizational capabilities European governments and firms acquired, and the political skills they honed, in the F-104 programme created the network of alliances and competencies that birthed not only Airbus, but also the SEPECAT Jaguar strike fighter, the Panavia Tornado, and the Eurofighter Typhoon,³³ as well as co-production of the General Dynamics F-16 Fighting Falcon, which together have replaced the F-104 Starfighter. The mystery for us should not be why technology does not change, but that it manages to do so at all.

¹Donald T. Campbell, "Descriptive Epistemology: Psychological, Sociological, and Evolutionary," From the William James Lectures of 1977 at Harvard

University, in Donald T. Campbell, *Methodology and Epistemology for Social Science: Selected Papers*, E. Samuel Overman, ed., Chicago, University of Chicago Press, 1988, Chapter 17, pp. 435-485, at p. 444. Compare Richard R. Nelson and Sidney Winter, *An Evolutionary Theory of Economic Growth*, Cambridge, MA, Harvard University Press, 1982, p. 10.

² Alfred D. Chandler, Jr., with Takashi Hinkino, *Scale and Scope: The Dynamics of Industrial Capitalism*, Cambridge, MA, Harvard University Press, 1990. Chandler's account of the rise of big business, or "the modern business enterprise," in his more fashionable phrase, is not nearly so grounded in a robust selection theory as he would like to believe. See Edward W. Constant II, "Limited Reach: the Visible Hand and the 'oil bidness' in Texas," in Mila Davids, Ferry de Goey, and Dirk de Wit, eds., *Proceedings of the Conference on Business History*, October 24 and 25, 1994, Centre of Business History, Erasmus University, Rotterdam, The Netherlands, 1995, pp. 44-60.

³ Ben R. Rich and Leo Janos, *Skunk Works: a Personal Memoir of my Years at Lockheed*, Boston, Little Brown, 1994.

⁴ This discussion of the F-104 is drawn from Martin W. Bowman, *Lockheed F-104 Starfighter*, Marlborough, UK, Crowood, 2000, unless otherwise noted.

⁵ William Green and Gerald Pollinger, *The Observer's Book of Aircraft*, London, Frederick Warne, 1958; William Green, *The Observer's Book of Aircraft*, London, Frederick Warne, 1974.

⁶ John W. R. Taylor, ed., *Jane's All the World's Aircraft, 1959-60*, Great Missenden, Bucks, England, Sampson Low, Marston & Co., 1959.

⁷ John W. R. Taylor, ed., *Jane's All the World's Aircraft, 1970-71*, Great Missenden, Bucks, England, Sampson Low, Marston & Co., 1970.

⁸ Green, note 5, 74

⁹ William Green, *The Observer's Book of Aircraft*, London, Frederick Warne, 1962.

¹⁰ Bowman, note 4, p. 27.

¹¹ John W. R. Taylor, ed., *Jane's All the World's Aircraft, 1965-66*, Great Missenden, Bucks, England, Sampson Low, Marston & Co., 1965, p. 254.

¹² *Ibid.*

¹³ *Ibid.*, p. 499.

¹⁴ Bowman, note 4, pp. 66-67.

¹⁵ With apologies to Bruno Latour and his "anti-programs." See Bruno Latour, "Where are the Missing Masses? The Sociology of a Few Mundane Artifacts," in Wiebe E. Bijker and John Law, eds., *Shaping Technology/Building Society: Studies in Sociotechnical Change*, Cambridge, MA, MIT Press, 1992, pp. 225-258.

¹⁶ Vincenti, p. 762

¹⁷ *Ibid.*

¹⁸ Jane's '65, p. 254.

¹⁹ Vincenti, note 13, p. 764.

²⁰ *Ibid.*, p. 764-765.

²¹ *Ibid.*, p. 763.

²² *Ibid.*, p. 765.

²³ Bowman, note 4, p. 19.

²⁴ *Ibid.*, pp. 17-19.

²⁵ Bruno Latour, "Where are the Missing Masses? The Sociology of a Few Mundane Artifacts," and Madeleine Akrich and Bruno Latour, "A Summary of a Convenient Vocabulary for the Semiotics of Human and Nonhuman Assemblies," both in Wiebe E. Bijker and John Law, eds., *Shaping Technology/Building Society: Studies in Sociotechnical Change*, Cambridge, MA, MIT Press, 1992, pp. 225-258, and pp. 259-264.

²⁶ For a complete actor-network explication of an aircraft project (which did not reach fruition), see John Law and Michel Callon, "The Life and Death of an Aircraft: A Network Analysis of Technical Change," in Wiebe E. Bijker and John Law, eds., *Shaping Technology/Building Society: Studies in Sociotechnical Change*, Cambridge, MA, MIT Press, 1992, pp. 21-52. For a similar approach to engine development, see John Law, "The Olympus 320 Engine: A Case Study in Design,

Development, and Organizational Control," *Technology and Culture* 33 (July, 1992): 409-440.

²⁷ Susan Leigh Star and James R. Griesemer, "Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-1939," *Social Studies of Science* 19 (May, 1989): 387-420. p. 387.

²⁸ Joan H. Fujimura, "Crafting Science: Standardized Packages, Boundary Objects, and 'Translation,'" in Andrew Pickering, ed., *Science as Practice and Culture*, Chicago, IL, University of Chicago Press, 1992, pp. 168-211; Susan Leigh Star and James R. Griesemer, "Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-1939," *Social Studies of Science* 19 (May, 1989): 387-420.

²⁹ Fujimura, *op. cit.*, p. 176.

³⁰ For a wonderful description of the mesmerizing effect of long, straight highways, see the opening paragraphs of Robert Penn Warren's *All the King's Men*

³¹ Others have noted the importance of technological stasis, but usually not for "modern" technologies. See Gerry Martin, "Stasis in complex artifacts," in John Ziman, ed., *Technological Innovation as an Evolutionary Process*, New York, Cambridge University Press, 2000, pp. 90-100.

³² Eva Jablonka, "Lamarckian inheritance systems in biology: a source of metaphors and models in technological evolution," in John Ziman, ed., *Technological Innovation as an Evolutionary Process*, New York, Cambridge University Press, 2000, pp. 27-40; Elizabeth Pennisi, "A New Look at Maternal Guidance," *Science* 273 (6 September 1996): 1334-36; James A. Shapiro, "Adaptive Mutation: Who's Really in the Garden?" *Science* 268 (21 April 1995): 373-374; J. Pablo Radicella, Peter U. Park, and Maurice S. Fox, "Adaptive mutation in *Escherichia coli*: A Role for Conjugation," *Science* 268 (21 April 1995): 418-420; Timothy Galitski and John R. Roth, "Evidence That F Plasmid Transfer Replication Underlies Apparent Adaptive Mutation," *Science* 268 (21 April 1995): 421-423.

³³ See "Eurofighter Typhoon – the Consortium," <http://eurofighter-typhoon.com/main/consort.htm>