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Quiet Contributor: The Civic Career and Times of John W. Tukey

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Abstract. Across 60 years, John W. Tukey contributed to the advancement of democracy, peace and industry via development, application and teaching of knowledge. In his nation's service, he contributed to the Nike missile defense, U-2 spy plane, surveillance satellites in space, hydrophones in the oceans, seismic data interpretation and communications code breaking. As computer and communication pioneer, Tukey collaborated with von Neumann, Shannon and Pierce; coined "bit" and "software"; applied statistical time series methods to processing signals; and recognized the usefulness of fast Fourier transform algorithms to digital processing of correlated data. Practical problems inspired Tukey to invent new ways to analyze data. As teacher and author, he made these available to others. Tukey advised government and industry regarding environmental quality, educational testing, the census, pharmaceutical efficacy, manufacturing quality and technologies for gathering intelligence. This paper explores the civic career, influences and philosophies of a practicing data analyst, inventor and remarkable public servant.

Key words and phrases: Exploratory data analysis, fast Fourier transform, time series, boxplot, stem-and-leaf display, multiple comparisons, analysis of variance, one degree of freedom for nonadditivity, robust estimates, software, bit, American Philosophical Society, Bell Labs, Brown University, Center for Advanced Study in the Behavioral Sciences, Central Intelligence Agency, Health Effects Institute, Institute for Advanced Study, Institute for Defense Analyses, Merck, National Security Agency, Princeton University, RAND, Presidential Science Advisory Committee, System Development Foundation, Xerox PARC, census, educational testing, election returns, environmental protection, CFCs, Nike missile, pharmaceutical testing, SOSUS, U-2 spy plane, Edgar Anderson, F. J. Anscombe, William O. Baker, Hendrik Bode, Arthur Burks, W. E. Deming, Richard Feynman, R. A. Fisher, William F. Friedman, Richard Garwin, H. H. Goldstine, I. J. Good, David C. Hoaglin, James Killian, Alfred C. Kinsey, Solomon Kullback, Edwin Land, Richard Leibler, Brockway McMillan, Oskar Morgenstern, Frederick Mosteller, Daniel P. Moynihan, Walter Munk, M. H. A. Newman, John R. Pierce, Edward Purcell, Claude E. Shannon, Lyman Spitzer, Jr., Alan Turing, Stanislaw Ulam, John von Neumann, John Archibald Wheeler, Norbert Wiener, Samuel S. Wilks, Charles P. Winsor.

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Owing to prolific interests, John W. Tukey challenges holistic appreciation. His good fortune to associate with so many issues and wonderful intellects of his age seems extraordinary. He illustrates that an energetic data analyst can serve a splendid diversity of issues and causes. In a world with no shortage of challenges, his career seems intrinsically heartening.

This paper will sketch Tukey's career, with emphasis on his consulting for industry and government. Such consulting inspired his contributions to data-analytic methods. I will also allude to some persons and circumstances that shaped him.

My perspective is that of a nephew, 40 years junior. John's wife Elizabeth and my mother were sisters, my father a colleague. (Tukey recommended my father's appointment on grounds he wanted a colleague to "talk to, not at.") Tukey saved a vast accumulation of professional paper. A skim through this archive has recently afforded me a much better sense of his diverse career.

Disclaimers are much in order. This paper is not about the substance of approaches to analyzing data. Even regarding Tukey's civic career, this is by no means definitive. A great deal about his career has been unknown to me and much remains so. By temperament, Tukey was self-contained and modest. He also operated on a discreet, "need to know" basis. Happily for the telling of history, John Archibald Wheeler has given posterity books recounting his experiences, Richard Feynman wrote engaging essays, Stanislaw Ulam a memoir. In contrast, Tukey wrote little about himself. He beavered away at technical issues, to the end. Many with whom he collaborated are no longer available to offer their insights. On the plus side for historians, Tukey saved a wealth of (unclassified) paper and gave four interviews.

My title draws from Tukey's homage to Samuel S. Wilks (1906–1964):

> A man instinctively so friendly and fair that everyone responded to him with great affection. His death terminates a quiet, penetrating, and influential leadership in the work of many organizations—especially in mathematics, statistics, and social science—to which he brought wisdom, commitment, persistence, and a remarkable sense of the importance of new developments. His passing leaves an emptiness in so many places that one wonders how one man was so versatile and did so much.... In his service to our Society, Sam showed all the wonderful characteristics we have noticed elsewhere: quiet, modest diligence, deep wisdom, a technical skill that was always adequate to any demand; the ability to comprehend, and bring others to comprehend, the broader issues. As members of Benjamin Franklin's own society, it is only right that we salute our departed friend as "Sam: A Quiet Contributor to Mankind" (Tukey, 1964).

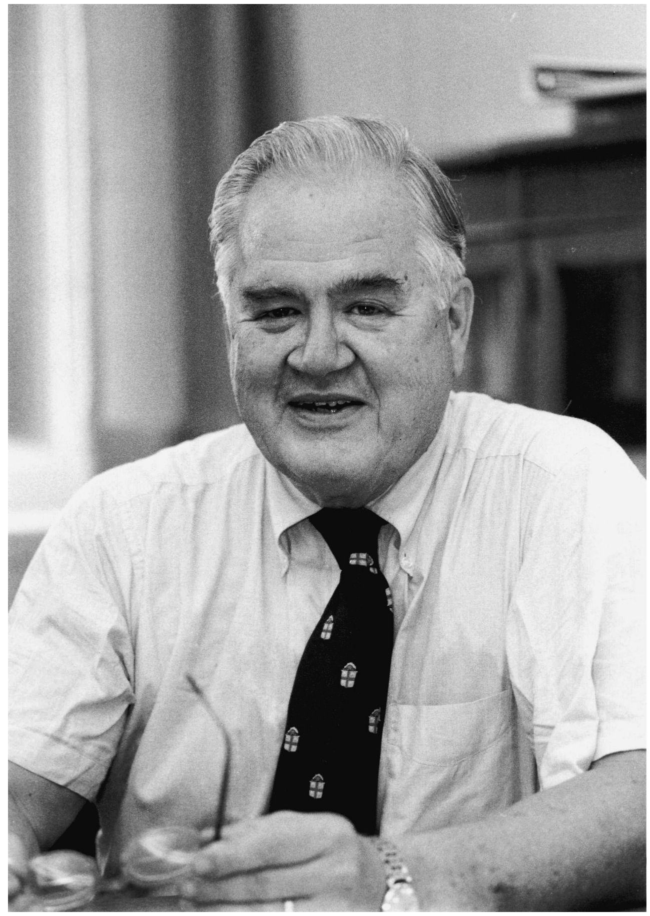

FIG. 1. *In his Princeton University office, 1984.*

BACKGROUND

John Wilder Tukey (1915–2000) was the sole child of Adah (Tasker) and Dr. Ralph Hermon Tukey. His parents met at Bates College in their home state of Maine, from which they graduated in 1898, ranked first and second. (They married in 1912, after Ralph's mother had died.) Their son evinced his New England heritage. John spoke with a "down-east" accent, offered few superfluous words and relished pie for breakfast and fish chowders. He displayed the Yankee traits of thriftiness—wearing one set of black polo shirts for 40 years—and of generosity, indicated by hearing out the many who sought his counsel. [“Harold Dodge was a New Englander of the best of the old style…economical with his money, but generous with time and advice” (Tukey, 1979).] His guiding “axiom number one” was that “people are different.” This expressed his ethical penchant for appreciating others as they were.

During the 1940s and 1950s, Tukey called folk dances. (A dance flyer reads: “Old timers and beginners are welcome to the YMCA Folk Dance Group at the Summit [New Jersey] YMCA.… This group has been meeting regularly during the season under the direction of John Tookey, well-known Princeton folk dance leader. Mr. Tookey and his friends will demonstrate steps for beginners. Newcomers may attend two sessions at 25 cents guest fee, following which they may register as members.”) Yet it was aptly said “his work is his fun” (Mosteller, 1984).

Tukey’s zest for scientific, technological and public issues evoked comparisons to another Princeton polymath, John von Neumann (1903–1957):

> John Tukey, like John von Neumann, was a bouncy and beefy extrovert, with interests and skills in physics and astronomy as well as mathematics (Wheeler, 1998).
> He ranks with such intellectual giants as Professor Henry Norris Russell, the dean of American astronomers, and Professor John von Neumann, the phenomenal mathematician-physicist (Eisenhart, 1955).

(Born in Budapest, von Neumann came to Princeton in 1930, shifting to the Institute for Advanced Study from 1933. He was among several historically significant Hungarians who emigrated during the 1930s, including Eugene Wigner, who also came to Princeton, Edward Teller and Leo Szilard. During 1927–1929, von Neumann developed a mathematical framework for quantum mechanics. In 1944, he joined Oskar Morgenstern to publish *Theory of Games and Economic Behavior*. From 1937, von Neumann was a scientific advisor to the Defense Department, spending much of 1943–1945 at Los Alamos. From 1944, computing was an abiding interest. In 1953, he led a Strategic Missiles Evaluation for the Air Force. Appointed a Commissioner of the Atomic Energy Commission in 1955, von Neumann received the Medal of Freedom in 1956.)

As a data methodologist, Tukey was opinionated and provocative. As I knew him, he seemed imperturbable, dutiful, physically powerful, loyal, good-humored yet serious of purpose, supportive, an incessant traveler, dignified absent elegance. He would acknowledge something was amusing by uttering a measured: “hah…hah.” He did not much engage in social talk; his wife was their designated conversationalist. Tukey liked to garden, sail, bird-watch and, from the 1970s, look at football, later golf, on television. When writing, he played recordings of classical music, favoring baroque brass. A signature characteristic was prolific reading of light fiction—mystery, science fiction and adventure stories. (Brown University Library has since accepted 12,000 books from his collection.) Another diversion was crossword puzzles. He needed to occupy his mind even in repose.

A further characteristic was jotting numbers, often in matrices. One had the sense of someone immersed in numbers and what “quick and dirty” analysis might reveal. Tukey worked with numbers like bodybuilders lift weights. His prodigious output owed to commensurate effort.

Another characteristic was to ask others what they were working on. This conveyed respect, empathy and willingness to help. Tukey was ever forward-looking:

> We’ve come a long way, but you wouldn’t expect me to feel satisfied, would you? In the next decade, statisticians can try to expand the variety of situations in which you get good performance—and maybe in the decade after that they can try to expand it again. How else can we get on with the world? (*Bell Labs News*, 1985).

Such foresight is mentioned by Tukey’s most frequent collaborator Frederick Mosteller:

> John always did two things: took a pass at the problem I asked him about and then he’d always suggest something else, something entirely different to work on. And I gradually got an important idea out of that experience, which was that it’s important to get out of ruts and into some new activity that may turn out to be more beneficial (Anscombe, 1988).

[Mosteller entered Princeton in the fall of 1939. World War II interrupted his studies. He returned to complete his thesis. Wilks was his nominal thesis advisor, yet unobtainably busy, thus Tukey advised Mosteller. In

1946, Mosteller began teaching at Harvard, where in due course he came to chair four different departments. (Fienberg, Hoaglin, Kruskal and Tanur, 1990)].

Tukey's manner was elliptical and enigmatic, Delphic Oracle in black polo shirt. (In contrast, his writing style was spare and direct.) Jimmie Savage quipped that if you asked JWT how to milk an elephant, he might think you were joking and decline to tell you. However, if you expressed a general interest in elephants, then Tukey might well get around to volunteering how to milk one. In other words, Tukey knew a great deal, but a direct question would often prove unfruitful.

At a party Tukey hosted in 1939 at the Nassau Tavern to celebrate completion of his Ph.D., milk was provided. Since Tukey's beverages of choice were skim milk or cider, he would have been at ease celebrating with milk in a tavern. Similarly, Tukey employed plastic Ziploc bags, conventionally used for food preservation, to organize his papers; this use practically suited his needs. Generally, John followed his own compass.

Because Tukey advised government leaders, some might wonder about his political views. My aunt would lament that he voted for Democratic candidates, offsetting her votes. Yet, Tukey's personal normative views were immaterial to his role; thus he was still valued by Republican administrations. He aimed to render sound technical advice to everyone. He did not try to persuade others to adopt his normative views. To have done otherwise would have violated the deference implied by "axiom number one."

Through 47 years of marriage, Elizabeth Tukey empowered John's career in numerous respects. When he took on too many commitments, she made him pare back or take a vacation. When he got sick, he was grounded. She managed their finances and houses. Married to a workaholic, she cultivated her own interests: collecting, appraising and selling antiquarian art, particularly botanical illustrations and Asian ceramics; and preservation of historic architecture. In relation to these interests, she enjoyed learning and sharing her knowledge. Fortunately for me and my siblings, she also took a caring interest in relatives, as well as in John's students and colleagues. She presumably bore his absences owing to appreciation that Tukey served society in valuable ways.

EDUCATION

Tukey's father earned graduate degrees in classics from Harvard and Yale, and taught at Hopkins Grammar School in New Haven and William Jewell College near Kansas City, before settling near Tasker relatives in Massachusetts. There, Ralph Tukey headed the Latin Department at New Bedford High School. Since a married woman could not then be a full-time teacher in Massachusetts, his wife, Adah, served as a "substitute." "Between the two of them, they ended up teaching everything in this high school, except book-keeping and physical education" (Tukey, 1985). John's broad learning may have been instilled early.

John attended few classes at New Bedford High (chemistry laboratory, French and mechanical drawing), being otherwise taught at home and via his own reading at the public library. During four years at nearby Brown University, John earned bachelors and masters degrees in chemistry, graduating in 1937. His education included "large doses of physics and substantial doses of geology," plus a class in topology by von Neumann's friend, Polish expatriate Stanislaw Ulam.

Many of Tukey's career pursuits seem derived from the fortuitous happenstance of moving to Princeton University. His intention was to continue in chemistry, yet Princeton was a world center for mathematics (Aspray, 1988) and Tukey gravitated toward this strength. The Bamberger family, New Jersey merchants, had endowed the Institute for Advanced Study. Opening in Princeton in 1933, the institute welcomed scientists from Europe, including Albert Einstein and mathematicians Kurt Gödel, von Neumann and Herman Weyl. Until 1939, the latter were co-located in the original Fine Hall with the university's mathematical contingent, including Solomon Lefschetz, Salomon Bochner, H. F. Bohnenblust, Alonzo Church, Albert Tucker and Sam Wilks.

> These two groups of outstanding mathematicians were so well integrated that, late in my second semester, Marston Morse, one of the giants at the Institute, could and did ask me, as a regular attendee at his course, "Are you at the University or at the Institute?" (Tukey, 1984a).... Since I was a chemist, I regarded that as an interesting question.... I went to probably more sets of lectures than a rational person would. But it did not seem to do any harm (Tukey, 1985).

Tukey's dissertation under Lefschetz was published as *Convergence and Uniformity in Topology* (Tukey, 1940). Receiving a Ph.D. in two years, more customary then than now, the 24-year-old began teaching at

Princeton in September 1939, an association that continued until age-mandated retirement in 1985.

While a student (Fall 1937–Spring 1939), Tukey shot 80 film rolls of campus life. He indexed pictures on filecards, as if foreseeing the value of a visual record of this academic community. Friends included future Nobel laureate physicist Richard Feynman, astrophysicist Lyman Spitzer, chemist and future business leader William O. Baker, musicologist Edward Tatnall Canby and postdoctoral mathematicians Frank Smithies and Ralph Boas. Economist Oskar Morgenstern was a member of this circle. Tukey had fun building a radio for Canby (Canby, 1980). He collaborated with Feynman, Arthur Stone and Bryant Tuckerman in folding paper into origami-like "hexaflexagons," for which they developed topological formulas. Stone and Tukey followed with theorems for sandwiches (Stone and Tukey, 1942). The first *Scientific American* column by mathematical journalist Martin Gardner belatedly brought minor celebrity to the hexaflexigators (Gardner, 1959).

Tukey teamed with Spitzer and Boas to submit spoof articles to serious journals, including a theorem of big-game hunting (Pétard, 1938). Putatively authored by H. Pétard, it was submitted by E. S. Pondiczery of Ong's Hat, New Jersey (a real albeit modest location). Feynman and Tukey jousted at numeric gymnastics and experimented to determine if they could perform two mental functions simultaneously (Gleik, 1992). Feynman counted while silently reading, whereas Tukey could count while reciting poetry aloud. Mosteller: "Night after night, Feynman and Tukey dazzled all who could crowd around at the Graduate School dinner" (Brillinger, 2002a).

Princeton was a small town, amidst verdant farmlands, endowed with a handsome campus. It is easy to envision pleasant camaraderie within the Graduate School, during halcyon days, on the brink of World War II. "Those were great days, days that contributed to all I have done since" (Tukey, 1984a).

WORLD WAR II

Danish physicist Niels Bohr visited Princeton in January 1939, bringing word of the revolutionary discovery by German scientists that the splitting of uranium atoms unleashed great energy (Rhodes, 1986; Wheeler and Ford, 1998). Later that year, Einstein wrote President Franklin Roosevelt to warn of this portent for atomic weaponry. In the years that followed, physicists and mathematicians from the university and institute contributed significantly to the Manhattan District Project. When this undertaking was revealed to the public in 1945, it was the chairman of Princeton's physics department who wrote the official report on atomic energy for military purposes (Smyth, 1945). Oswald Veblen, who profoundly shaped mathematics at Princeton, advised the Army's Ballistic Research Lab through both world wars. This overall context seems relevant. Tukey joined a university at which many were then devoted to meeting challenges facing their nation and its values. Woodrow Wilson's credo of his university's mission—"in the nation's service"—had much currency.

Hitler's invasion of Poland spurred civilian science leaders to gird for the conflict ahead. Carnegie Institution President Vannevar Bush (Zachary, 1997), Harvard's James Conant, Bell Labs' Frank Jewett, Cal Tech's Richard Tolman and MIT's Karl Compton conceived of a National Defense Research Council (NDRC) to harness the innovatory genius of civilian scientists. Nearly 10,000 draft deferments were awarded for NDRC service. As first NDRC head, Bush advised President Roosevelt to commit resources to the atomic bomb, radar and many other technologies.

The NDRC formed an Applied Mathematics Panel that included Merrill Flood, Thornton Fry, Saunders Mac Lane, Mina Rees, John von Neumann, W. A. Wallis, Warren Weaver and Sam Wilks. Wilks in turn steered the Statistical Research Group–Princeton. Personnel included, at nearby Columbia University, T. W. Anderson, Albert Bowker, Churchill Eisenhart, Milton Friedman, Abraham Girshick, Cecil Hastings, Harold Hotelling, Frederick Mosteller, Jimmie Savage, Herbert Solomon, George Stigler, Abraham Wald, Jacob Wolfowitz (father of Paul, the current deputy secretary of defense) and, at Princeton, George W. Brown, Wilfrid Dixon, A. M. Mood, David Votaw and John D. Williams:

> Sequential analysis was just one of the many innovations that came out of Wilks's statistical research groups during World War II.... One of Wilks's objections to the mathematicians who continued to inhabit their world of pure abstractions was that they were not being patriotic. He felt the country needed the brainpower they were siphoning into these purposely useless abstractions. This brainpower needed to be applied, first to the war effort and then to the Cold War thereafter (Salsburg, 2001).

Starting in May 1941, six months prior to U.S. entry into World War II, Tukey served Princeton University's Fire Control Research Office. Headed by Merrill Flood, colleagues included Corneil Messler, Brockway McMillan, Lawrence Rauch, Albert Tucker, Audrey Wishart and Charles P. Winsor, an "engineer-turned-physiologist-turned-statistician" (Tukey, 1978):

> We worked together most of World War II, talking over most meals, and during many evenings, so that I had a chance to learn much that a statistician should know that was not then in the books—and I suspect some that is not yet in them. As a result, the first time that I was in a statistics course, I was there to teach it. I can only guess how much of my later statistical work stems from many, many discussions with Charlie (Tukey, 1984a).

Tukey worked on stereoscopic height and range finders for antiaircraft guns, which involved optics and atmospheric effects. He addressed rocket powder, fire control from tanks and tactics for B-29 bombers. Tukey "stimulated" topologist Leon Cohen on calculating leads for shooting at planes (Mac Lane, 1989). B-29 collaborators included Flood, Irving Segal and Henry Eyring. During these years, the flavor was, of course: "do crucial applications, and any mathematics that can help" (Tukey, 1978). This philosophy guided Tukey ever after.

In January 1945, Tukey was hired by Bell Labs. The Air Force engaged AT&T to develop a defense against high-flying bombers. W. A. McNair, Hendrik Bode, Tukey, G. N. Thayer and B. D. Holbrook conceived the world's first surface-to-air missile defense, Nike, named after the goddess of victory in Greek mythology. Tukey and Holbrook addressed "aerodynamics, trajectory, and warhead" (Tukey, 1985). An AT&T history:

> The report was considered a classic because of its insight and scope covering a wide spectrum of disciplines from propulsion and guidance to prospective aerodynamics and because of the small amount of time (five months) required to complete an in-depth study that formed a solid conceptual basis for the five years of R and D work that followed (Fagan, 1978).

Three years later, Bode wrote that Tukey had:

> a great fertility in ideas, open-mindedness toward heterodox solutions, and penetration in reaching the heart of complex and abstruse situations. These are wedded to unusual energy, which permits him to carry out two or three times the load of ordinary men. It is safe to say that he has made an irreplaceable contribution to the national defense.

Bode served as best man at Tukey's 1950 wedding to Elizabeth L. Rapp, personnel director of the Educational Testing Service.

Following Nike's conception, Wilks persuaded Tukey to return to Princeton, on a part-time basis. Merrill Flood has reported that Tukey asked him to develop a game-theory strategy for bombing Japan. Tukey "once hinted to Flood that it had something to do with a mysterious flash that had been reported in the New Mexico desert. The study was, of course, for the Manhattan Project" (Poundstone, 1992). The first nuclear explosion took place on July 16, 1945, near Alamogordo, New Mexico, three weeks prior to the bombing of Hiroshima. If Flood's recollection and Tukey's hint were accurate, then in July 1945 Tukey had finished the Nike study and was again serving the NDRC. Bombing tactics occupied its Statistical Research Group throughout the war.

ENIGMA

William O. Baker has divulged that Tukey was "active in the analysis of the Enigma system" (Brillinger, 2002a). Baker would seem a credible source as "perhaps the most important member of the very secret National Security Agency's Scientific Advisory Board" (Bamford, 1982). Enigma was an encypherment system of the Nazi military that converted a text into a sequence of numbers, with the pattern of conversion changing. Yet there was some regularity by which the encrypting machine changed codes. Statistical techniques (multiple comparisons, sequential analysis, Markov chains) could be employed to decrypt messages (Hinsley and Stripp, 1993). The high volume of messages created vital need for automated help.

On the eve of World War II, Britain's Government Code and Cypher School (GCCS) did not have any mathematicians. One of the first to join was the deeply original Alan Turing (1912–1954). Inspired by a 1934 lecture by Cambridge topologist M. H. A. Newman, Turing envisioned a machine for "computable numbers." In May 1936, Newman became aware that

Princeton's Alonzo Church had written a related paper and steered Turing toward study with Church. During his second year at Princeton (Fall 1937–Spring 1938), foreseeing war with Germany, Turing discussed cryptanalysis with a student from Canada and crafted an electric calculator (Hodges, 1983). The same year, Newman also visited the Institute for Advanced Study. (Ironically, Newman's surname at birth was Neumann.) Upon earning his Ph.D., Turing was offered a job at the institute by von Neumann, who touted Turing's "brilliant ideas" to Ulam in early 1939 (Hodges, 1983). However, Turing returned to England and promptly became affiliated with GCCS. With the outbreak of war in September 1939, Turing joined the code-breaking effort at Bletchley Park, as did other mathematicians.

Helped by Polish mathematicians who replicated an early-generation Enigma machine, Bletchley was reading many messages by 1941. This intelligence helped vital convoys to evade U-boats. After the Nazis modified their encryption in early 1942, Newman, having also moved to Bletchley, conceived of an approach to automated decryption, using a Boolean logic computer. From late 1942, Bletchley was again reading many messages, which had a significant impact on Allied military success. Another involved was I. J. "Jack" Good, subsequently a significant contributor to Bayesian statistics (Salsburg, 2001). (For Good's career: http://ei.cs.vt.edu/~history/Good.html.)

There seem plausible avenues via which Tukey could have contributed to U.S. efforts on Enigma. Before the war, Wilks worked with Bell Labs mathematician Thornton Fry (Tukey, 1985). Bell Labs began to develop a digital coder of voice communication in 1936, under Walter Koenig. The NDRC's communications division addressed speech secrecy, providing a contract to Bell Labs (Kahn, 1996). During 1942, Turing spent two months at Bell Labs working on Koenig's secure phone (later used by President Roosevelt and Prime Minister Winston Churchill). In Washington, Turing met Princeton's Robert Greenwood, who knew many at Bletchley and Tukey from their Brown days together (Greenwood, 1984). In December 1942, the Army contracted with AT&T to build a computer for decoding Enigma messages (Budiansky, 2000).

Given the value of Cambridge mathematicians to Bletchley, it would seem unsurprising if the Army's Signal Intelligence Service had sought out mathematicians at Princeton. Ace code-breaker Solomon Kullback wrote *Statistical Methods in Cryptanalysis* in 1938. A bookseller description:

> This classic text provides various statistical tests: the Chi Test, which affords a quantitative measure of the degree of similarity between two distributions, and the Phi Test, which provides a quantitative measurement of the degree of non-randomness of a distribution. Text includes numerous tabulations of frequency data in other languages.

During 1938, foreseeing the collision course with Hitler, could there have been discussions of code breaking at Princeton among Wilks, Fry, von Neumann, Veblen and Newman, with ramifications for younger men like Turing, Good, Baker, Greenwood and Tukey, among others? If so, it was a secret that participants did not divulge to my knowledge, perhaps to protect secrets with ongoing relevance. If he did contribute in some way to Enigma, Tukey may have harbored feelings like those of I. J. Good:

> Most of the cryptanalysts in the Newmanry [at Bletchley] dispersed into various universities and most of us achieved some measure of success in our unclassified work. But the success of our efforts during the war, and the feeling that we were helping substantially, and perhaps critically, to save much of the world (including Germany) from heinous tyranny, was a hard act to follow (Good, 1993).

After Bletchley, Newman moved to the University of Manchester, where he received Royal Society funding to develop a computer. He was joined by Good (1945–1948) (before his return to code breaking) and Turing (1948–1954) (before his suicide, following revocation of his security clearance on a charge of indecency; loss of his clearance curtailed Turing's opportunities to work in the computing age he had done so much to advance). In 1997, Newman's son wrote Tukey: "I have a photograph above my desk of you, my father, and about 50 other mathematicians at the Princeton bicentenary [1946]. It's a source of inspiration to me!" (A similar picture is available at: www.math.uiuc.edu/People/princeton_photo.html.)

WELLSPRINGS

Sir Ronald Fisher's contributions to statistical methods during the 1920s and 1930s were prompted by agricultural experiments at Rothamsted Experimental Station. Tukey was inspired by applied problems at

Bell Labs, "The World's Greatest Industrial Laboratory" (Bello, 1958), Princeton and via consulting to industry and government:

> Since World War II, I have spent part-time at Princeton and part-time at Bell Laboratories, 30 miles away in Murray Hill—so in a very real sense, what I am is what Princeton and Murray Hill have made me. I had very helpful guidance from S. S. Wilks and W. O. Baker, both of whom I met during my first year at Princeton. This was aided, of course, by a touch of Washington, DC and by many contacts with scientists and technologists in a wide diversity of fields (Tukey, 1984a).... Many of the real innovations were stimulated by particular data sets or by the subject-matter problems of particular friends and colleagues. It is not too easy to get such catalysis—the relative frequency of stimulation is often quite low—but I am sure that I would have found it harder, and less rewarding, to sit in a pure theorist's ivory tower, and invent the problems that needed to be solved (Tukey, 1984b).

Elizabeth R. Tukey:

> Over the years, I have suggested to John that perhaps he should take seriously one of the many job offers he received; and move from Princeton. His reply was always the same: "Where could I ever find another Bell Labs?" Because we have always lived in Princeton, it has been easy for friends and colleagues to think of John in terms of the University only. So perhaps, tonight I have...helped to underline the opportunities, resources, and recognition that the Labs have bestowed on him.... Bill [Baker] was a behind the scenes advisor to the government not only on scientific policy, but also on persons who could contribute their expertise to help formulate and promote the policies.... Bill's seconding of John to all sorts of jobs was both masterful and astute. It suited John's taste for interesting problems to solve and very interesting people, with a great diversity of talents, to associate with" (E. R. Tukey, 1997).

Bell Labs chairman William O. Baker:

> John Tukey's thinking is so fine and fast that his host of friends and admirers are forever asking him to do it again.... John has had an incisive role in each major frontier of telecommunications science and technology: uses of transistors and the solid state; digital coding and computers; statistical strategy for finding how speech energy is distributed in frequency (an essence of telephony, leading also to important concepts which he named: "prewhitening," "aliasing," "tapering," "cepstrum"); evolution of software and operations support systems; earth satellite and other microwave techniques; electronic switching; laser-based photonics; topology of integrated circuits; adaptation of behavioral and human-factors science to telecommunication. Collaborating with John in these and a multitude of other missions, I have known his warm and heartening friendship and his unerring assessment of human abilities and temperaments. He has joined in conceiving and organizing most of the initiatives in communications principles and science research undertaken at Bell Labs since 1955.... We have watched at least four Presidents of the United States listen to John and heed his counsel (*Bell Labs News*, 1985).

Nobel laureate physicist Arno Penzias:

> Bell Labs has had many outstanding scientists, a smaller number of great scientists, and a few great scientists who are also great people. John is one of these—a great scientist who is also a great man. Few have had a role equal to his in shaping the information age (*Bell Labs News*, 1985).

COMPUTING PIONEER

Princeton and Bell Labs both positioned Tukey to contribute at the dawn of electronic computing. The best-known contributions were semantic. In 1946, Tukey is said to have coined "bit" (short for binary digit). Brockway McMillan:

> A group of us at Bell Laboratories, probably over lunch, were discussing the awkwardness of, and the hint of internal inconsistency in, the term binary digit. We deplored the lack of a suitable substitute. John Tukey

> joined us at about this point, and heard our complaint. With a characteristic grin, and equally characteristic down-east inflection, he asked, "Well, isn't the word obviously bit?" And it was. Several persons must have been present, but memory identifies only Tukey; he disclaims any recollection. Inference points strongly to R. W. Hamming, and to Claude Shannon perhaps, as witnesses (McMillan, 1984).

Shannon first used "bit" in print in *A Mathematical Theory of Communication* (Shannon and Weaver, 1949).

Tukey is further credited with first use of "software" in a 1958 article (Shapiro, 2000):

> Today the "software" comprising the carefully planned interpretative routines, compilers, and other aspects of automative programming are at least as important to the modern electronic calculator as its "hardware" of tubes, transistors, wires, tapes and the like (Tukey, 1958).

When this was reported, I phoned Tukey. He was typically noncommittal. He did not mention that he recalled coining software, despite the quotation marks that surrounded his use of the word. Nor did Tukey mention that he drew on a word already in spoken use. This obscurity seems consistent with McMillan's account of how he disclaimed "bit."

An earlier invention of "software" may come to light, since the term seems inevitable in relation to computing machinery. Yet, in his teachings Tukey coined many words. This proclivity was indicative of his need to invent a vocabulary to match his statistical creativity and to support his arguments. So if it were to stand the test of time that Tukey was the first to coin "software," it should not be surprising.

In 1939, Tukey and McMillan bought parts "with the intention of putting up a one-bit's worth of what would now be a central processor, since the world was drifting toward computers. It was never assembled, which shows we were not deeply committed to it" (Tukey, 1985). Tukey would have later opportunities.

The first electronic computer, ENIAC, was developed in 1944 at the University of Pennsylvania (McCartney, 1999), funded by the Army's Ballistic Research Laboratory. ENIAC's Army contact, Herman Goldstine, encountered von Neumann at the Aberdeen, Maryland, train station and informed him about this computer. Within a few months, von Neumann was thinking about a teleological society to study "communication engineering, the engineering of computing machines, the engineering of control devices, the mathematics of time series in statistics, and the communication and control aspects of the nervous system" (Goldstine, 1972). Envisioned members were to include Sam Wilks, W. E. Deming of the Bureau of Census, MIT's Norbert Weiner and Goldstine.

During late 1945, von Neumann convened a team to design an electronic computer for the Institute of Advanced Study. Tukey was the only staff member of the university who participated in this team. He is thanked in the preface to the resulting report (Burks, Goldstine and von Neuman, 1946). Arthur Burks:

> Tukey designed the electronic adding circuit we actually used in the Institute computer. In this circuit, each binary adder fed its carry output directly to the next stage without delay. As I recall, experimental measurement showed that the complete carry took about 4 clock pulses. And this was the circuit actually used because it was reliable and much simpler than the alternative (Brillinger, 2002a).

Also involved were RCA's Vladimir Zworykin and J. A. Rajchman, statistician George W. Brown and ENIAC veterans Burks and Goldstine: "A logical design for the machine...was done by Burks and me, in collaboration with von Neumann and assists from John Tukey" (Goldstine, 1972). Thus, what is commonly known as "von Neumann architecture" seems shorthand for "Burks–Goldstine–von Neumann–Tukey architecture."

Military funding drove the early development of computers. Another early computer recipient was the nuclear weapons laboratory at Oak Ridge, Tennessee. During the early 1950s, Tukey visited with sufficient frequency to form a folk dance group. Later, Tukey may have advised the National Security Agency on its unmatched computing infrastructure. During the 1970s, he advised Brown, Dartmouth and Princeton on their computing needs.

Tukey invested much effort during the 1960s, enlisting statisticians around the country, to develop a *Citation Index of Statistics and Probability*. Reprints stuffed 120 file drawers; entry sheets were keypunched. Five resulting volumes, with Jim Dolby and Ian Ross, seem a forerunner to databases considered essential today for law, medicine and other complex fields. Tukey's project bespeaks regard for those in his profession, providing a resource by which to cope with the growth of their literature.

During the 1990s, Tukey received nine patents pertaining to methods for automated information retrieval, in association with colleagues at Xerox's Palo Alto Research Center (PARC). This seems in keeping with his lifelong quest for finding useful information. It seems unsurprising that, despite "retirement," he would work on search strategies for browsers before many had heard of the Internet. John Seely Brown, PARC's director, reported that Tukey provided "wisdom and encouragement, coaching and mentoring" (Brillinger, 2002a).

NATIONAL SECURITY

In October 1945, the Air Force launched Project RAND, later RAND Corporation, in Santa Monica, California. RAND (short for Research and Development) had links to Nike. AT&T selected Douglas Aircraft (later McDonnell Douglas) to design the Nike missile, booster and launcher, a partnership that lasted 30 years. RAND was first staffed with Douglas personnel, though it came to serve generally as a think tank for Air Force strategies. (In 1969, RAND spun off a System Development Foundation, which later awarded \$80 million in research grants; Tukey advised this foundation for years.)

RAND drew mathematicians, who employed game theory and Monte Carlo analysis. From Princeton, von Neumann, Tucker and Tukey were part-time consultants and referred students, including John Forbes Nash (four decades later to share an economics Nobel prize for a game-theory paper). From RAND, Nash penciled a question to Tukey, who relayed an answer from Alonzo Church. George W. Brown, Merrill Flood, Alex Mood, Melvin Peisakoff and John D. Williams joined full-time. In a 1947 RAND report, Tukey's friend Lyman Spitzer "accurately predicted that a satellite would be able to spot and track the movement of ships at sea" (Taubman, 2003, page 63).

Tukey "spent a fair amount of my Murray Hill time in connection with Nike for quite a long time." Fall 1946 found him at the White Sands Missile Range observing missile firings. During the next two decades, Nike components were developed and upgraded, before an antiballistic-missile (ABM) pact with the Soviet Union brought an end to defensive missiles. All told, the Nike program produced 358 ground batteries and 14,000 missiles.

Nike spurred "Linearization of Solutions in Supersonic Flow" (Tukey, 1947). Important contributions to time series analysis with great practical value to signal-processing technologies (Tukey and Hamming, 1949; Tukey, 1950a) arose "from the need to know how much airplane flight paths were likely to be disturbed by atmospheric wind gusts" (Tukey, 1984b). (A second inspiration was the meteorology data of Hans Panofsky.) Drawing on thinking by Norbert Wiener, Tukey's power spectra work—statistical methods for indirectly discriminating underlying signal from clutter—thereafter conferred much usefulness by serving such diverse technologies as sonar, radar, seismic and medical. These procedures were made broadly available via publication of *The Measurement of Power Spectra from the Point of View of Communications Engineering* (Blackman and Tukey, 1959).

Stepping back, some broader contexts seem illuminating. Until his death in 1953, Stalin ruled the Soviet Union. During his reign, he killed millions of his subjects. In August 1949, the Soviet Union exploded a fission bomb. Two weeks later, communists completed conquest of China. In June 1950, communist North Korea invaded South Korea.

Against this backdrop, in December 1950, Tukey's former instructor Stanislaw Ulam conceived a design for a fusion (hydrogen) bomb. During early 1951, John A. Wheeler enlisted Tukey (Wheeler and Ford, 1998), among others, in mathematical evaluation of this design:

> After Edward Teller and Stanislaw Ulam got the idea that finally made the American bomb possible, it fell to Wheeler and his people to do many of the basic computations. Computing facilities being what they were, it sometimes took 36 hours on the machines to carry out some of the work. It was these computations that persuaded Oppenheimer that the new design was, in his indelible phrase, "technically sweet" (*Princeton Alumni Weekly*, 1985).

Between 1951 and 1956, Tukey's curriculum vitae indicated that he served as "Supervisor, Military Systems Analysis," at Princeton's Forrestal campus. During the 1950s, Tukey frequently lunched with physicists Lyman Spitzer, Martin Schwarzschild and John A. Wheeler. An amateur mountaineer, Spitzer conferred the name Project Matterhorn on the university's nuclear research programs. Spitzer headed energy research, Wheeler that on weapons. Tukey dubbed their group the "Chowder and Marching Society." (Their wives also formed a social group, presumably discussing different topics.)

In July 1952, Tukey spent a week in England. He saved an engraved invitation to lunch with Lord Cherwell, Churchill's science advisor during World War II. The same year, Tukey signed a consultant agreement with the research arm of the Central Intelligence Agency (CIA).

Disappointed by communications interception during the Korean War, President Truman formed the National Security Agency (NSA) in November 1952. The next month, Tukey, von Neumann and Wilks joined its Science Advisory Board (SAB). "Twice a year the SAB would converge on Fort Meade, join with senior NSA scientists, and...discuss application of the latest theories in science and technology to eavesdropping, code-breaking, and cryptography" (Bamford, 1982). Other SAB members included William O. Baker, Cal Tech's Robert Dilworth, Honeywell's Joseph Eachus, Illinois' Stewart Cairns, GE's Richard Raymond and RAND's Willis Ware (Bamford, 1982).

The NSA's research head was Solomon Kullback, one of several responsible for breaking Japanese codes during World War II. Author of *Information Theory and Statistics* (Kullback, 1959), "Kully" became a professor of statistics at George Washington University after retirement in 1962. Tukey corresponded with Kullback. Tukey's phone lists held entries for Lou Tordella, who became NSA's deputy director in 1958. Tordella's tenure until 1974 marked a period during which the NSA established worldwide eavesdropping capabilities.

Returning to broader perspectives, the United States detonated a fusion weapon in the fall of 1952. Nine months later, the Soviet Union tested its own hydrogen bomb. The Soviet Union developed long-range bombers and missiles that offered the prospect of devastating surprise attack. Desperate for information on Soviet military intentions, the United States felt obliged to send surveillance flights over the Soviet Union. Several hundred airmen sacrificed their lives in this cause, yet little useful information was gleaned (Taubman, 2003).

Taking office in 1953, President Eisenhower reached out for fresh thinking about the crucial problem of reliable intelligence about the Soviet military so as to prevent a surprise nuclear attack. Eisenhower selected MIT President James Killian to head a 42-man Technical Capabilities Panel from academia and industry to address America's vulnerability. Bell Labs contributed James Fisk as Killian's deputy, Brockway McMillan and Tukey.

One result was conception of the U-2 spy plane, which the Central Intelligence Agency (CIA) began to fly above the Soviet Union in 1956. Light-weight and long-range, the U-2 flew at 70,000 feet, above air defenses, equipped with a high-resolution camera. Later results were the SR-71 Blackbird supersonic spy plane that could outrun air defenses and the first space-based reconnaissance satellite, Corona.

Tukey spent the fall of 1954 participating in Killian's panel (Richelson, 2001; Taubman, 2003). He belonged to a small subgroup devoted to intelligence. Edwin Land, inventor of Polaroid Corporation's instant photography, was its head. Others were engineer Allen Latham, formerly of Polaroid; astronomer James G. Baker and physicist Edward Purcell, both from Harvard; and Washington University chemist Joseph W. Kennedy. Baker designed a sophisticated camera lens for the U-2. During the Manhattan Project, Kennedy had isolated plutonium; his context may have been detection of nuclear weapon tests. A radar expert, Purcell received a Nobel in 1952 in relation to nuclear magnetic resonance (Buderi, 1996).

Why was Tukey included? His prior work entailed optics, radar, astronomy, atmospheric conditions and supersonic airflow. He may also have contributed in relation to communications interception, code breaking, photointerpretation and evasion of air defenses. Known for its camera, the U-2 was also equipped with electronic receivers:

> Scores of antennas, like small blades, were attached to the fuselage, each dedicated to particular frequency bands.... The U-2, said one CIA report at the time, possesses altitude capabilities which make it a unique platform for the reliable acquisition of high quality telemetry data prior to first stage burnout on Tyuratam [Soviet missile center] launchings. Such data is of extreme importance in determining ICBM [intercontinental ballistic missile] characteristics (Bamford, 2001).

In March 1955, Killian wrote Princeton's President Dodds:

> The work of the panel is classified and therefore the efforts of the Panel members must remain untold in terms of the kind of work which they did. I can say to you,

> however, that Dr. Tukey drew upon his insight and abilities as a mathematician and a statistician to join in important creative developments in one of the most pressing aspects of our national program. We are fortunate to have had him as part of the Panel group.

Tukey hid a roster of panel members inside the pocket of a nondescript checkbook. After his death, only careful search revealed this memento.

Killian's work was far from over. In 1956, Secretary of Defense Charles Wilson asked him to establish "a means by which government may tap the reservoir of scientific talent represented by the nation's academic institutions." Killian's answer became the Institute for Defense Analyses (IDA), a nonprofit think tank formed by a consortium of Cal Tech, Case, MIT, Stanford and Tulane (IDA, 1960). Owing to student opposition to the Vietnam War, formal links between the universities and IDA ended in 1968. IDA has executive officers, backed by trustees. Tukey served as an IDA trustee during the 1980s and 1990s. I do not know when his service began.

In 1957, the Soviet Union shocked the American public by launching an earth satellite, Sputnik. One reaction was formation of the Defense Advanced Research Projects Agency (DARPA), later noted for its support for development of the Internet. IDA hired top scientists and engineers for DARPA. From Princeton another reaction: Wheeler, Morgenstern and Nobel laureate mathematical physicist Eugene Wigner proposed a study group of scientists "with a strong interest in the defense of the country" (York, 1987). By 1960, their idea became IDA's Jason group.

English cryptologist I. J. Good visited Princeton during October 1955. Good visited Bell Labs, where he lectured on a species sampling problem and on terminology of information theory to an audience that included Shannon. Tukey traveled to England on Defense orders (July 27 to August 15, 1955; June 7 to August, 1956; December 1 to December 11, 1956). These trips probably included meetings with the NSA's English counterpart and Good's employer, Government Communications Headquarters, Cheltenham. The NSA and Cheltenham coordinated, with one or the other focusing on different geographic regions (Bamford, 2001). On June 17, 1956, Tukey dined with Nobel laureate physicist Sir John Cockcroft, director of the Atomic Energy Research Establishment, Harwell.

President Eisenhower commissioned a panel akin to Killian's earlier one for the purpose of charting a course for the National Security Agency. Its chair was William O. Baker, then vice president for research at Bell Labs. From a photo, it is reported that Baker's team included Nobel laureate physicist Luis Alvarez, MIT's David Huffman and Oliver Selfridge, Harvard's Andrew Gleason, IBM's Richard Garwin and Hendrik Bode, John R. Pierce and Claude Shannon from Bell Labs (Bamford, 1982). Little has been reported about the Baker panel. It must have conceived plans for intercepting Soviet communications and decoding them via computing, statistics and information theory.

By 1958, Killian was chairman of IDA. After the Baker panel completed its work, IDA formed a think tank dedicated to the NSA. To house this Communications Research Division (CRD), IDA built von Neumann Hall on Princeton's campus, which opened in 1960 (Bamford, 1982). In October 1958, the NSA's Richard Leibler convened a meeting at the Nassau Tavern to solicit academics to engage in classified research. Tukey, Wilks, Gleason, Huffman and Selfridge were among 23 attendees. A six-man "Focus" advisory committee to the NSA was established, headed by Hendrik Bode, with Tukey and Wilks as members.

CRD's first director was Cornell's J. B. Rosser, followed by Chicago's A. A. Albert. Between 1963 and 1977, Leibler headed the NSA's Princeton affiliate. Like Kullback and Tordella, Leibler has been recognized in a hall of honor for NSA employees (available at http://www.nsa.gov/honor/leibler.html). (One condition of recognition is that honorees have not participated in cryptological work for 15 years.) Kullback and Leibler collaborated on a statistics paper (1951). Leibler spent 1946–1948 studying at the Institute for Advanced Study in Princeton. During 1948–1949, he developed theoretical work that proved useful to the Venona program (Haynes and Klehr, 1999).

During World War II, the Soviet Union took advantage of its alliance with the United States to engage in extensive military and industrial spying (Rhodes, 1995, Chapter 5, "Super Lend-Lease"). Venona decrypted Soviet diplomatic messages, unmasking such espionage agents as Julius and Ethel Rosenberg, Bill Weisband, David Greenglass, Harry Gold and the English traitors Klaus Fuchs, Guy Burgess, Donald Maclean and Kim Philby (Benson, 2001). Such intelligence could not be made public at the time. With the encouragement of Senator Daniel Patrick Moynihan, in 1995 the National Security Agency released 3000 decoded Venona communications (available at http://www.nsa.gov/docs/venona/venona_docs.html).

During the late 1950s, Wilks chaired the NSA's Science Advisory Board. He recommended Kullback for membership in the Cosmos Club. William F. Friedman, who started the Army Signals Intelligence Service in 1930, attended the opening ceremony for von Neumann Hall. Friedman talked with Wilks about donating his cryptologic history collection to Princeton. Through the years, Wilks had been sounded out about other jobs, including presidency of the University of Texas. Nevertheless, the native Texan continued his Princeton-based callings. In March 1964, after 26 years of collaboration with Tukey, Wilks died in his sleep, a sudden grievous loss. Twenty-one years later, Tukey still felt regret for not having attended a meeting before Wilks' death, in case he could have forestalled an argument in which Wilks became embroiled (Tukey, 1985).

In 1970, CRD had 27 staff, mostly mathematicians on academic sabbatical, and 33 support personnel. That year, students objected to the presence of the NSA's affiliate. Tukey wrote to Princeton president Robert Goheen on CRD's behalf, to no avail. Thereafter, CRD found another location in Princeton, off university property. In 1976, the NSA's headquarters received the first Cray supercomputer; a second was delivered to CRD in Princeton (Bamford, 1982).

The Tukeys never mentioned CRD to me. In hindsight, I assume John had an office there. The Princeton location made sense. Princeton was a center for mathematics; code breaking drew on mathematics and statistics. Nearby Bell Labs had experts in communications engineering and secrecy systems. Tukey had a foot in each institution, fostering collaboration. William O. Baker: "John was part of our force in the Fifties which did the really historic work on the Soviet codes. He was very effective in that whole operation" (Brillinger, 2002a). In 1996, Baker wrote to the Tukeys:

> One of the earliest missions that we undertook at the direct request of President Eisenhower is now being assessed by a group of historians at Fort Meade as a major turn in military affairs.... John's part in this and so many other patriotic tasks is unsurpassed.

Tukey applied time series techniques to airplane dynamics (Press and Tukey, 1956). In 1959, he joined Nobel laureate physicist Hans Bethe in Geneva to support a State Department team, headed by James Fisk of Bell Labs, negotiating with the Soviet Union on an end to underground tests of nuclear weapons. As with any treaty, verification was crucial. Was it possible to distinguish an underground explosion from an earthquake? Tukey wrote papers inspired by this context (Tukey, 1959; Bogert, Healy and Tukey, 1963).

Tukey saluted Scripps Institute oceanographer Walter Munk as his "strongest source of catalysis...for new techniques or new understandings" in time series (Tukey, 1984b). Yet they wrote no papers together. For the Navy, Bell Labs developed an acoustical surveillance network of hydrophones, the Sound Surveillance System (SOSUS), to track sounds given off by Soviet submarines armed with nuclear weapons. Walter Munk:

> My field, oceanography, has greatly benefited by John's interest and his style. In the 1940s, no one in oceanography understood the concept of power spectra and random phases, yet most ocean processes are random-phase. We tried to fit ocean surface wave spectra by a few lines with stable phases (a la tide predictions with which we were familiar). The difference is fundamental. As typical of him, John made it a point to understand, in detail, what I was trying to do, not just the mathematical procedure, but an understanding of the underlying physics. This certainly led to a total change in ocean wave work. It eventually led to a revolution in oceanographic data analysis.

By the 1970s, SOSUS was exploiting "the Cooley–Tukey fast Fourier transform algorithm. This provides great flexibility in selecting frequency resolution and analyzing bandwidth in the generation of power spectrum estimates" (Fagan, 1978, page 477). During early 1963, Tukey wrote lectures for a graduate-level class on the frequency analysis of time series (Tukey, 1984c). These notes include a fast Fourier transform (FFT) algorithm, two years before formal publication (Cooley and Tukey, 1965).

Between 1960 and 1963, Tukey served on the President's Science Advisory Committee (PSAC) (Herken, 2000). At a PSAC meeting during 1963, Tukey showed FFT algorithms to IBM's Richard Garwin. Recognizing their practical value, IBM swiftly assigned programmer James Cooley to work with Tukey to harness FFT into software.

The immediate context of Garwin and Tukey would likely have been the processing of acoustic and seismic signals for national security purposes. Yet FFT quickly had far wider ramifications as well. It has since proven to be one of the most useful algorithms of modern times, ushering in digital signal processing to supplant analog equipment. In so doing, FFT has served such diverse needs as weather forecasting, spacecraft guidance and medical diagnostics. Our society is reliant on the processing of informational signals. The benefits accruing from FFT have been profound.

Tukey's FFT paper provided only two citations, one a paper by I. J. Good. In a 1997 letter, Good recalled Tukey visiting him on December 6, 1956, when Good mentioned a fast way to do Fourier analysis. Garwin also visited Good, in September 1957. Garwin later wrote to Good: "Had we talked about an FFT in 1957, I could have stolen it from you then, instead of from John Tukey in 1963."

For his part, Tukey mentioned a similar algorithm invented by graduate student Gordon Sande, which did not receive sufficient recognition. In a fuller sense, FFT built on work pioneered by Fourier and Gauss 150 years earlier, and the algorithm had been independently discovered several times during the 20th century. What finally ushered in practical adoption was Tukey bringing FFT to the attention of computational experts at IBM. Good, Tukey, Garwin and Cooley found contemporary uses for venerable ideas.

During his PSAC service, Tukey also evaluated the West Ford system. Conceived at MIT's air defense lab, West Ford entailed placement of 400 million copper filaments in earth orbit to reflect radio signals for interception. (Such passive systems were superseded by satellites.)

The Kennedy administration established a National Reconnaissance Office in 1961 to coordinate satellite espionage by the Air Force and CIA. Its very existence was classified for more than 30 years. Brockway McMillan headed NRO during 1963–1965. In 1966, the outgoing head of the CIA's Science and Technology Directorate, Albert Wheelon, wrote Tukey that his successor "would appreciate, as I have, your strong support to the scientific and technical programs of this Agency." In 1986, CIA director William J. Casey:

> Thank you for your excellent report on the intelligence implications of the Strategic Defense Initiative. The report does a commendable job of scoping the problem. To paraphrase what I believe to be your assessment, it is difficult to judge what the impact on intelligence will be without making some assumptions to limit costs and/or technology. Otherwise, the envelope of possible solutions grows to unrealistic proportions. I agree completely. Your statements of the potential areas to limit the problem seem comprehensive.... I feel certain your report will affect the way we do business in the future.... I look forward to more such excellent work.

In 1993, CIA director James Woolsey invited Tukey to become an emeritus member of the CIA's Science and Technology Advisory Panel.

When I was a child, I had in mind that Tukey worked for the phone company, happily helpful for my aunt, who so liked to use the phone. This view was partly correct. A bit later, I came to envision Bell Labs as a well-funded place where eggheads studied their curiosities. This may have had some elements of truth, but no longer seems the whole story. Bell Labs also served national security and business issues.

Service to the NSA, CIA, RAND, IDA, Atomic Energy Commission, DARPA, President's Foreign Intelligence Advisory Board, Army, Navy and Air Force did not appear on Tukey's curriculum vitae. "I have often said, to a few intimate friends, that most people have never realized that John had a third job [beyond Princeton and Bell Labs]—that of giving his expertise to an array of U.S. government agencies" (E. R. Tukey, 1995).

Tukey's duration and breadth of service to national security matters were probably unusual. Much about his service will likely remain murky, deliberately so on his part. Tukey was likely privy to many aspects of U.S. intelligence gathering. Discretion preserved secrets and personal security. As someone excused from the firing lines of a war, perhaps he felt a special onus. Surely he would have enjoyed contributing to serious matters, as he did across many fields of human endeavor.

In a big-picture sense, the intelligence-gathering architecture conceived during the 1950s subsequently helped to protect the United States and its allies from nuclear holocaust. This provided time for liberalizing influences to take root in Russia and China. Late in life, Eisenhower confided to Killian: "This bunch of scientists was one of the few groups that I encountered in Washington who seemed to be there to help the country and not help themselves" (Taubman, 2003). This seems true of Tukey. When he encountered an idea with commercial implications, fast Fourier transform, he rushed it into the public domain to speed its adoption.

"The productive collaboration between the government and science, which carried over into the Kennedy administration, was sundered by the Vietnam War. It has never been fully rebuilt" (Taubman, 2003). Tukey was not sundered. He also served the federal government on environmental protection, the census, educational testing and arms control. He likely viewed it his civic responsibility to contribute his best advice, whatever the topic.

ARCHITECTS OF THE COMMUNICATION AGE: CLAUDE E. SHANNON, JOHN R. PIERCE AND JOHN W. TUKEY

In 1948, Pierce, Shannon and Tukey submitted a patent application for a cathode ray device, one indication of their closeness. Tukey's contributions deserve to be viewed in conjunction with Shannon and Pierce. While beyond my scope, this topic seems worthy of research.

Pierce (1910–2002) is credited as the father of communications satellites. From 1930, he wrote science fiction stories, many under the pen name J. J. Coupling. He wrote an accessible introduction to information theory (Pierce, 1961). From 1958, Pierce was the director of communications principles at Bell Labs. Tukey was assistant director of communications principles (1958–1961), before becoming associate director of information sciences (1961–1985). The two men shared a love for science fiction; their professional connections seem many and profound. After retiring in 1971, Pierce affiliated with Stanford University's Center for Computer Research in Music and Acoustics, which received a $2.7 million grant from the (Tukey advised) System Development Foundation. Pierce studied how sound is processed by the ear and brain.

Shannon (1916–2001) is esteemed for "A Mathematical Theory of Communication" (1948) regarding which he was indebted to Norbert Wiener, as was Tukey for time series. Shannon spent 1940–1941 at the Institute for Advanced Study, working under Hermann Weyl, before moving to Bell Labs to work for Thornton Fry on antiaircraft fire control, a topic with which Tukey was similarly occupied. Tukey coined "bit" for Shannon's concept. In 1949, Shannon helped introduce Tukey's work on power spectrum estimates for communications engineering. Fresh from the Baker panel on the NSA, Tukey and Shannon both spent 1957–1958 at the Center for Advanced Study in the Behavioral Sciences. Thereafter, Shannon moved to MIT, though he continued part-time affiliation with Bell Labs until 1972. At MIT, Shannon was honored as a Donner professor, as was Tukey at Princeton. In 1955, Tukey energetically lobbied Congress in support of citizenship for Hermann Weyl.

Tukey worked on statistical techniques needed by communications engineers to design equipment that processed signals. Shannon developed underlying mathematical theory for communications. Yet, out in the unruly real world, signals are subject to distortions, creating uncertainties for which statistical solutions were required. Shannon and Tukey seem complementary contributors in fostering the communication age.

Shannon pedaled a unicycle while juggling through Bell Labs, invented a rocket-powered Frisbee and composed poetry. Pierce knew fellow science fiction writers Isaac Asimov, Ray Bradbury and Arthur C. Clarke. Shannon, Pierce and Tukey were each interesting characters and accomplished scientists on their own. They also merit collective consideration.

HEALTH AND ENVIRONMENT

On behalf of the American Statistical Association, Tukey joined Cochran and Mosteller in evaluating Indiana professor Alfred Kinsey's controversial research on male sexual behavior (Cochran, Mosteller and Tukey, 1954). The trio saw Kinsey's notoriety as an opportunity to convey better methods to social scientists. Their book balanced praise with constructive suggestions on how to conduct surveys. [Mosteller and Tukey continued to serve psychologists thereafter (Mosteller and Tukey, 1968).]

Tukey advised pharmaceutical companies, especially Merck, with which he enjoyed association for 48 years (1952–2000). He made suggestions about the design of clinical tests (Tukey, 1977b) and published eight papers with Merck scientists (Brillinger, 2002a). During the 1960s, Tukey was involved in the National Halothane Study that considered possible association between halothane anesthesia and postoperative hepatic necrosis.

One major health issue of modern times has been the effects of smoking. During the 1950s, such eminent statisticians as R. A. Fisher, Jerzy Neyman and the Mayo Clinic's Joseph Berkson were skeptical of studies that linked cigarettes to lung cancer. In 1956, Tukey wrote the National Cancer Institute's Jerome Cornfield, inviting him to Princeton to confer with F. J. Anscombe and M. Wilk about statistical methods useful to his organization. Three years later, Cornfield collaborated with five physicians on an influential paper that supported the linkage between smoking and lung cancer (Cornfield, 1959). While I have no basis for attributing aspects of Cornfield's paper to lessons obtained during his visit to Princeton at Tukey's invitation, this possibility warrants research.

An inveterate bird-watcher, Tukey served pollution issues. In the wake of Rachel Carson's *Silent Spring*, he chaired a Presidential Science Advisory Committee (PSAC) panel (1964–1965) that wrote *Restoring the Quality of Our Environment* (Tukey, 1965b). Its oft-cited principle: "The responsibility of each polluter for all forms of damage caused by his pollution should be effectively recognized and generally accepted. There should be no 'right' to pollute." Tukey also chaired another PSAC panel (1971–1972) that authored *Chemicals and Health*:

> We must always live with some risks, both because nature forever confronts us with hazards, and also because the contributions of chemicals to human welfare are so vital. Our knowledge is never complete; as it increases, it will make us reconsider, and often revise, past decisions (Tukey et al., 1973).

During 1975–1979, given Nobel prize–worthy concerns raised by Rowland and Molina about erosion of the earth's stratospheric ozone shield, Tukey chaired three National Research Council reports on the potential effects of chlorofluoromethane carbons (CFCs). National Academy of Sciences president Philip Handler:

> Now that we have gone public and you are a TV star, the time has come for me to convey the appreciation of the Academy. Truly do I believe that the nation and the Academy can count themselves fortunate that your integrated intelligence, insight, sound judgment, good taste, and unflappable reasonability were all available to take the halocarbon report safely through the many shoal waters.

Tukey served the President's Air Quality Advisory Board (1968–1971) headed by Aarie Haagen-Smit and a task force that evaluated the herbicide 2,4,5-D (dioxin). He advised the National Oceanic and Atmospheric Administration (1977–1979) and the National Acid Precipitation Assessment Program (1989–1996). From 1981 to 1992, he served the Health Effects Institute (HEI), founded by William O. Baker, Archibald Cox and Donald Kennedy to evaluate the potential health effects of automotive exhausts. Tukey offered advice regarding the design of HEI studies. These likely have since proven useful for defining air quality criteria.

In 1990, Senator Daniel Patrick Moynihan wrote Tukey that revision to the Clean Air Act "explicitly and for the first time builds cost benefit analysis into environmental law. A half century hence this could well be regarded as the most important feature of the entire bill." Moynihan and Tukey likely shared a view that pollution issues deserved to be looked at in a full and balanced way, from multiple perspectives.

DEMOCRACY, EDUCATION AND INDUSTRY

Between 1960 and 1980, Tukey analyzed voting data for NBC News. Richard Scammon was the on-camera interpreter of politics, while Tukey steered analysis of returns, in conjunction with Richard Link, Robert Abelson, ENIAC co-inventor John Mauchly, David Wallace and David Brillinger. In 1960, they may have saved NBC from declaring Richard Nixon the winner in a close contest with John Kennedy.

Tukey was involved in debate about the census of 1980 and that of 1990. He testified before Congress and in litigation on behalf of cities whose citizens were uncounted. New York's Mayor David Dinkins: "I am grateful for your extraordinary contribution of time and intellect to this critical issue."

For many years, Tukey chaired the Analytical Advisory Committee to the National Assessment of Educational Progress (1963–1982). He also long consulted to the Educational Testing Service (1965–2000). Tukey spent 1957–1958 at the Center for Advanced Study in the Behavioral Sciences, starting a partnership with its director Ralph Tyler on educational testing. From 1980 to 2000, he served the center's Advisory Committee on Special Projects.

Tukey served as a member of Brown University's Board of Fellows from 1974 to 1988, while also contributing to the university's computer and library committees. He served Princeton's scheduling committee from 1950 to 1970; he was renowned for solving scheduling problems in his head, often while lying on his back so as to be comfortable while thinking.

After World War II, Tukey imparted lessons to manufacturing firms through the Society for Quality Control, whose early members included W. E. Deming, Sam Wilks, Walter Shewart and Harold Dodge. In 1948, Tukey helped Deming, then with the Office of Budget, send quality control literature to Japan. In the decades that followed, Deming became acclaimed for contributions to Japan's industrial prowess. Tukey's relationship with Deming probably inspired a two-part paper on improving federal statistics (Tukey, 1949a, b).

During 1970–1971, Tukey served on a Presidential Commission on Federal Statistics, headed by Allen Wallis.

Tukey consulted to Exxon across decades. During the late 1950s, he consulted to a uranium-mining firm. He also served the causes of individuals. During the early 1950s, he rallied support for the head of the National Bureau of Standards who had been unfairly removed.

WRITINGS

A prolific author, Tukey wrote two books, coauthored 14 others. In addition, there are eight volumes of "Collected Works" containing 141 papers. Among these were 39 previously unpublished papers, including "Measuring Noise Color" (1949), "The Sampling Theory of Power Spectrum Estimates" (1950) and "The Problem of Multiple Comparisons" (1953), which circulated in mimeograph for 40 years, as though samizdat. Why would such valuable papers have been unpublished? Tukey enjoyed challenges and was ever turning to his next one. In addition, some papers provided direct technological benefits that may have been company proprietary or national defense sensitive. The *Collected Works* was predicated on the need to make past work more available.

Collected Works seems an optimistic misnomer. It should be termed "Selected Works." The editors considered, but did not include, 237 unpublished papers or presentations and 200 published ones. Additional unpublished papers inevitably eluded the editors and Tukey kept writing for another 15 years.

The *Collected Works* provides a 400-entry bibliography. Yet, in addition to these writings, Tukey produced about 400 more unpublished papers, 200 published ones, plus course materials and presentations. Even allowing for more than 100 co-authors, this outpouring seems extraordinary.

Two noble attempts to summarize Tukey's writings:

> The breadth and impact of his writings are stunning. Whole areas of statistics have had their foundations laid and others are inspired—spectrum estimation, multiple comparisons, quick and dirty methods, exploratory data analysis, graphics, robust methods, and Monte Carlo. The list of applications to science and technology goes on and on.... Raw brilliance is everywhere—the fast Fourier transform, stem-and-leaf diagrams, coining the word bit, one degree of freedom for non-additivity, components of variance, the jackknife, Tukey's Lemma, binomial probability paper, 3RSRH, and so on (Cleveland, 1988).

> Like Picasso going from cubism, to classicism, to ceramics, to fabrics, John Tukey marched across the statistical landscape of the second half of the twentieth century, from time series, to linear models, to generalizations of some of Fisher's forgotten work, to robust estimation, to exploratory data analysis. From the deep theory of mathematics, he emerged to consider practical problems, and finally to consider the unstructured evaluation of data. Wherever he put his mark, statistics was no longer the same (Salsburg, 2001).

TEACHER

The son of teachers, Tukey was, transcending all else, a teacher. Through 47 years of part-time service at Princeton, he oversaw the dissertations of more than 50 Ph.D. students. Tukey was gratified to consider their students in turn to be his "grand students" who in turn educated "great grand students." Some became long-term collaborators, essentially regarded as family members. Brillinger's impression was that Tukey "put students down a bit when they were over-cocky, and built them up when they were down." This rings true.

A man on a mission, Tukey spent much time on the road, spreading his lessons via talks at universities, conferences and "short courses." His final book was written with Australian Kaye Basford (Basford and Tukey, 1998), his penultimate volume with Stephan Morgenthaler of Switzerland (Morgenthaler and Tukey, 1991). Tukey's network was diversely international. (His home held 22 foreign language dictionaries.)

Innumerable authors forwarded manuscripts. Tukey frequently provided comments, sometimes by letters, sometimes by phone. Via such reviews, Tukey's influence extended beyond his own writings. "He seemed to want the result, not the credit" (Brillinger, 2002a). I have noticed about 50 books from diverse fields—econometrics, political science, numerical graphics, psychology—in which Tukey is thanked in the preface. Tukey encouraged unusual interests. In 1946, he supported Milton Babbitt's dissertation on the mathematics of the 12-tone system, 46 years before Princeton's Music Department conferred his doctorate.

Since there were not textbooks for what he wanted to teach, Tukey developed course materials from scratch. These evolved into *Exploratory Data Analysis*. Teaching took place in diverse settings. A hectic schedule sometimes required combining students with weekend gardening. Tukey was noted for imparting useful information via scribbles on available paper, often restaurant napkins. (Some napkins were later framed.)

WORK METHODS

"Boundaries between disciplines, organizations, and people never lasted long in his mind, for he thought in terms of bridges, entrances, and opportunities" (Mosteller, 1984). Watching Tukey review four manuscripts during a short train ride, Wilks marveled: "He ate them up like peanuts" (Mosteller, 1984). Tukey was facile at multitasking, working on papers during seminars, while comprehending the speaker. A 1948 appraisal from mathematician William Feller:

> Tukey is rich in ideas, has a fifth sense for new possibilities, and develops an infinite amount of energy. He works almost at the same time on supersonic flow, computing machines, theoretical statistics, and special biometrical problems. The main value of his papers lies in the lucid exposition and ease with which Tukey popularizes new ideas and combines methods and results from different fields.

The Rockefeller Foundation's Warren Weaver (1948, a year before he introduced Shannon's epic work):

> From my extensive and direct personal contacts with John Tukey's work since 1940, I would, without any hesitation whatsoever, put him in the very front rank of American mathematicians of his age group. He is soundly and deeply trained in pure mathematics, he has a real appetite and ability to apply mathematics to useful and practical problems, he has really extraordinary energy and imagination.

Richard Hamming:

> Three or four years after I joined [Bell Labs], I discovered Tukey was slightly younger than I was. John was a genius and I clearly was not. I went storming into Bode's office: "How can anybody my age know as much as John Tukey?" Bode leaned back, put his hands behind his head, grinned slightly: "You would be surprised how much you would know if you worked as hard as Tukey." In effect, Bode was saying "Knowledge and productivity are like compound interest." Given two people of the same ability and one person works ten percent harder, he will more than twice outproduce the former (Hamming, 1986).

Tukey drafted papers and correspondence by hand. His pen never left the page when writing, one efficiency. Tukey was blessed to be served by able people, including Eileen Olszewski and Mary Bittrich, who typed his work. He was likewise fortunate to collaborate with many co-authors. "John loves to work with others and many have had the pleasure of participating in his genius" (Mosteller, 1984). Collaborations enabled Tukey to bolster his output. Handwritten manuscripts are credited to "____ and J. W. Tukey." In due course, Tukey would enlist a lead author. This freed him for new projects, while the collaborator finalized a manuscript for publication.

ASKING THE RIGHT QUESTION

Tukey saw his duty as offering "annoying, but true statements." These upset current understanding, but were key to future advances. Similarly: "Far better an approximate answer to the right question, which is often vague, than an exact answer to the wrong question, which can always be made precise" (Tukey, 1962). Tukey was ever skeptical. This was termed "helping to keep someone honest."

On the teacher/student relationship, Tukey noted: "whether or not we kick them in the face, we must stand on the shoulders of others." Thus he respected, even when he disagreed. Tukey met R. A. Fisher during the latter's visit to the United States in 1946. Tukey benchmarked and honored Fisher by preparing an index to his writings (Tukey, 1950b). Tukey seemingly had in mind that his life mission would be to improve techniques to analyze data, as Fisher had done. During their courtship, he said something about this intention to Elizabeth Rapp. (This may not have helped advance his wooing, however, because she had not before heard of Fisher.)

During the mid-1950s, Tukey pursued Fisher to explain his theory of fiducial inference. Much of their correspondence has been revealed from the Fisher archive. It shows two colorful personalities. Tukey relentlessly challenged Fisher's theory via polite questions, the student beseeching the master to clarify his confusion. During a 1956 visit to England, Tukey visited Fisher to continue the topic in person. By then, the irascible Fisher had heard enough, but my aunt was present. Ever the gentleman, Sir Ronald took himself off, rather than show both Tukeys to his door.

EXPLORATION

One swerve from Fisher was exploratory data analysis. *Exploratory Data Analysis* (1977a) seems a radical book. Eschewing complex mathematics, its target audience was generously egalitarian and humane: anyone. Tukey appreciated that simple devices like the boxplot or stem-and-leaf display could offer value to the great majority of people who are not mathematically accomplished. The merit of an analytic method depended on serving the needs of people. He championed soundly conceived pictures that "force us to notice what we never expected to see." Tukey regarded data like a detective examining clues in his many mystery stories. Detectives cannot conduct experiments by repeating crimes, rather must interpret observed clues. Whereas Fisher developed methods for experiments, Tukey served observational contexts. (Three successor books in the "exploratory" vein were Hoaglin, Mosteller and Tukey, 1983, 1985 and 1991.)

Tukey dedicated *Exploratory Data Analysis* to biometrician Charles Winsor (1895–1951), who taught him during World War II, and to Washington University's Edgar Anderson (1897–1969), who served the Missouri Botanical Garden. Tukey met Anderson soon after Winsor's death. Anderson had reached out to Fisher during the 1930s for statistical advice and to some extent felt his needs as a biologist unmet. During the 1950s, Anderson found Tukey very helpful (Kleinman, 2002). He mailed Tukey cheery postcards from Ethiopia and Columbia, from the frontlines of his distant sojourns to seek knowledge about our biosphere's endowment of plant species. The two men shared a joy in exploring the unknown wonders of nature.

SCIENTIFIC UNIFIER

Tukey appreciated that "scientific and technological advances have made the world we live in complex and hard to understand." Increasing knowledge begets increasing specialization and narrower scope of understanding. He envisioned a college curriculum that aimed to produce "scientific generalists" (unifiers):

> Statistics, as the doctrine of planning experiments and observations and of interpreting data, has a common relation to all sciences. Unification will be more easily attained if the logical framework of the individual sciences can be identified and isolated from their factual content (Bode, Mosteller, Tukey and Winsor, 1949).

The curriculum had four semesters in biology, five in chemistry, four in statistics, six each in mathematics and physics, two each in psychology and English, one in geology and one in industrial processes. With Tukey in mind, John A. Wheeler has saluted the "scientific generalist":

> The imaginative statistician, far from being a narrow specialist, is often the direct opposite—a generalist: a man who can walk into almost any scientific or commercial operation, find a numerical way to analyze what is going on, and increase output.... The gains to the economy and productivity of a country—any country, at any level of industrialization—from such mathematized use of intelligence are so great compared to the cost involved that a sound and imaginative statistical generalist ranks high among heavy intellectuals (Wheeler, 1994, page 263).

THE SIMPLE SOLUTION

Economist Julian Simon's favorite Tukeyism: "If it is not worth doing superficially, it is not worth doing at all." In other words, the first step in diagnosis should be simple appraisal. Recalling experiments with Feynman, Tukey said: "We were interested and happy to be empirical, to try things out, to organize and reduce to simple things what had been observed" (Gleik, 1992). Tukey's homage to Harold Dodge suits himself:

> His commonsense was outstanding, as was his desire to penetrate to the bottom of the matter at hand. He loved the simple solution, both for itself and because it would be used, but he would never consider a simple "solution" that would not work.... His papers were typical of his style, simple and to the point (Tukey, 1979).

CAREFUL THOUGHT, BALANCED JUDGMENT

Tukey was mindful of the civic duty of citizens to resist the siren call of simple solutions that were false (what economists term "free lunches"). Addressing New Bedford High School:

> Most of the time each of you will have to act or speak out in haste—and it is right that this be so, for none of us has time to think hard about many questions. But we must do this with an appreciation that careful thought and a balanced judgment are important, that the big problems require as much of it as can be found.
>
> This means that you must be responsible for balanced judgment at second hand—and even at third—as well as for your own balanced judgment.... Ours is a society with a great division of judgment. We depend on our governments, Federal, State, and local for many judgments—some made by judges, some made by assembled representatives and by mayors, governors, or presidents, some made by those who carry out more detailed responsibilities, perhaps in the local municipal building or in some Federal building in Washington.
>
> You owe it to yourself, and to all your fellows, near and far, to take your part in this division of judgment seriously, to play your part in helping to have more balanced judgment and less taking of what seem, almost always falsely, to be easy ways out.... Some of this seems quite natural to us. We all recognize that crossing the street is dangerous—and that living our lives on a single block is unacceptable. That riding in an automobile is dangerous, but that walking everywhere is rarely a solution. We try to balance our risks and our gains, our costs and our benefits.... Each of you has the opportunity to be a single small voice speaking out—both in conversation and when you vote—for balanced judgment and for people who will strive for balanced judgment (Tukey, 1974).

CHANGE

> The Chinese have a curse: "May your children live in interesting times!"... This means that there have been problems, there are problems, and there will be problems, many of them very serious. It was once fashionable to believe in progress and the near utopia that would soon be with us. Then it was fashionable to say that the world was horrible and getting much more so with inevitable rapidity. I tell you that it is not true that problems will soon disappear and equally not true that they will get much, much worse. They will change, which means that we will always be replacing familiar problems—problems we know something about tackling—by new ones that we do not yet know how to deal with. The most painful things are not the problems, but the need to find new ways of thought, new things to be done, and new kinds of social organization. The need to change is ever painful, and it is the essential feature of interesting times (Tukey, 1974).

THROUGH THE GLASS, DARKLY

> I tried to inform you this morning about some of my concerns about uncertainty and the public at large; how uncertainty can be managed, but not eliminated; how every measurement, no matter how precise it is, suffers from a fuzz of uncertainty; how trying to evade uncertainty's presence can lead any of us astray; and how, since risks can never be wholly eliminated, we must learn to balance one risk against another. None of these concerns are easy tasks, but important for each alone and for all of us together (Tukey, 1984a).
>
> The creative analyst of data must...be prepared to live insecurely, to live with errors and fluctuations of uncomfortable size, not to forget or ignore them.... The necessary combination of opposing attitudes—required insecurity about the actual results, required security within the guiding mathematical studies—challenges our personalities in a way that few human endeavors do (Tukey, 1965a).

THE EVOLUTION OF DATA ANALYSIS

> A century ago, the field of physics was thought to be in the doldrums, because

there was nothing left but to "measure everything to another decimal place." We know how poor a forecast that was. Physics, particularly in recent decades, is neither just a science, nor just a technology. Like other vital fields of knowledge, physics is a scientific technology, blending aspects of science with those of craft.

If data analysis is to be a scientific technology, how will it have to differ from what is usually purveyed today? Very crucial, perhaps, are:

- a broader scope for "confidence," encompassing, for example, more kinds of uncertainties, in particular the uncertainties represented in what is often called sensitivity analysis.
- a recognition that serious queries are not likely to be answered by "point estimates." Intervals, often rough, are usually essential.
- above all, a recognition that expert judgment has an important role in structuring the analysis—and indeed a recognition that two experts can sometimes reach opposite conclusions from the same data.

This last point is often related to a recognition of some analyses as approximations to—or "short cut" substitutes for—more detailed, more complex, or more obviously appropriate analyses. How far we go down such paths does not have a single "correct" answer. Skill, experience, and judgment have to be included in choosing an analysis whose conclusions can be wisely accepted. What we routinely do in one decade may not be acceptable in a later decade.

Flexibility and evolution are both essential if we are to have a data analysis field worthy of being a scientific technology. In comparison with what is now current education (or indoctrination), we will have to greatly reduce the practice of hiding meaningful uncertainties in conventional assumptions and become used to being much more explicit about what might actually be going on, especially some activity which we have not been accustomed to allow for (Tukey, 1998).

CLOSING

John W. Tukey was a good-humored, forward-looking iconoclast, devoted both to practical problems and to teaching. A crusading, creative scholar, with altruistic aims, he was deeply educated in mathematics, yet knew much about technologies, the physical sciences and assumptions underpinning scientific methods. He perceived the borders of data analysis and expanded them. With his death, more than one statistician felt, "now we are on our own," since Tukey had been a valuable sounding board and source of encouragement.

Tukey defies easy summary. His interdisciplinary interests spanned from the lithosphere to the ether, with many stops in between. Some activities were confidential; his style could be indirect and enigmatic; collaborations sometimes shroud specific contributions. Yet, it seems clear that Tukey was a conscientious teacher, hardworking, skeptical, loyal, generous, a team player, contributing whatever the team needed: ideas or encouragement. He valued careful thinking and balanced judgment to cope with intrinsic uncertainty. He knew we are fated to live during "interesting times" and that change may be painful, yet is necessary. He pursued the quest for "honesty," for discriminating valid insights at the shadowy frontiers of knowledge.

Among his honors, Tukey received seven honorary degrees, the National Medal of Science, the Institute of Electronic and Electrical Engineers (IEEE) Medal of Honor and foreign membership in the Royal Society of London. This paper has been my effort to understand what he did to warrant these generous accolades. My best answers are that Tukey's contributions to processing signals have conferred inestimable benefits. In defense applications, they may have helped to deter devastating attack. They have also been incorporated into technologies that serve lives in everyday ways. Tukey's perspectives on analyzing data and his prolific methodological inventions ripple in many directions.

Now that I better understand his career, I better understand his equanimity. His busy life entailed exposure to many talented people tackling serious issues. Tukey had witnessed much. Since his death, the confused election of 2000 and surprise attack of September 11, 2001, were reminders to me that he contributed to relevant matters.

John A. Wheeler has said: "I believe that the whole country—scientifically, industrially, financially—is better off because of Tukey and bears evidence of his influence." I am persuaded to agree. At the same time, my intent has been to recognize circumstances that influenced Tukey and some of the many people, sung and unsung, to whom he was indebted. No man is an island, penned John Donne. Nevertheless, inspired and inspiring individuals do matter. This essay salutes one who "was so versatile and did so much," in concert with so many.

> History teaches—and even the brief history of the Institute confirms—that new knowledge leads to new power and new wisdom, and alters the destiny and heightens the dignity of man.—*J. Robert Oppenheimer* (Goldstine, 1972).

ACKNOWLEDGMENTS

John W. Tukey was understated about himself. As one of his executors, I feel an onus to communicate what I have learned or glimmered of his civic contributions. Where I have provided quotations without references, the source is usually the professional papers of Tukey or Sam Wilks at the American Philosophical Society (held at Philadelphia for the Advancement of Useful Knowledge). Tukey's papers are presently unavailable; it will take some years to organize and catalog them. I am grateful for comments from D. R. Brillinger, D. C. Hoaglin (Tukey's literary executor), K. Kafadar and H. Wainer. All errors are mine alone. I am further indebted to Professor Brillinger for papers regarding Tukey, which include insights from W. O. Baker and Arthur Burks; to Professor Munk for Tukey's contribution to oceanographic data analysis, and C. S. Smith. I regret that my story gives too little mention to the many statisticians with whom Tukey collaborated. To do them more justice would have complicated this story beyond my ability to tell it, in so far as I have.

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