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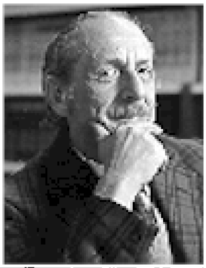

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The Most-Cited Papers of All Time, *SCI* 1945-1988. Part 2. The Second 100 *Citation Classics*

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The second group of 100 most-cited papers in the 1945-1988 *Science Citation Index*® (*SCI*®) is presented. Nineteen Nobel laureates are listed among the 201 authors in this essay, and they account for 15 papers. This brings the numbers of Nobel authors and papers to 32 and 28, respectively, through the *SCI* Top 200. The *Journal of Biological Chemistry* again is the leader with 14 papers here and 31 overall.

Introduction

A few months ago, we identified the 100 most-cited papers in the 1945-1988 *Science Citation Index*® (*SCI*®).[1] That essay was the first of a series that is planned to cover the top 1,000-1,500 papers. The complete list will effectively represent the highest impact articles of modern science, a "citation elite" drawn from about 175 million cited references in some 15 million source items published over the past 44 years. The top 1,000-1,500 will represent just 0.004 percent of the approximately 33 million unique publications that were cited from 1945 to 1988.

Books are not included in this series but will be discussed separately in future essays. Citations to books are less standardized than article citations and require time-consuming editing and verification. Also, books often appear in several editions and languages, and each edition may be cited differently. It takes considerable effort to unify all of the possible citation variants and identifiable errors. In a future essay, we'll review the subject of citation errors that escape the journal editor's attention and cannot easily be "corrected" by ISI®'s quality control algorithms.

The Second 100 Most-Cited Papers Ever

Table 1 presents the second group of 100 most-cited papers in alphabetic order by first author's name. Column A gives the number of citations in the 1945-1988 *SCI* for each paper. Its rank among the top 200 follows in column B. Column C lists the average annual citations per paper—that is, total citations divided by the paper's age. For papers published prior to 1945, the annual average is calculated over the 44-year citation period covered by the 1945-1988 *SCI*. Column D gives 1988 citations, which can indicate whether a paper's current impact is rising or falling against its lifetime average.

Full bibliographic references for each paper follow the tabular information. An asterisk indicates that the paper was discussed in a *Citation Classic*® commentary. The issue, year, and edition of *Current Contents*® (*CC*®) in which the commentary was published appear in parentheses following the reference. To date, half of the 200 most-cited papers have been discussed by the authors themselves in *Citation Classic* commentaries—50 on papers listed in this study and 51 from Part 1.[1]

Tortoises and Hares

The oldest paper in Table 1 was published in 1924 in the *Journal of Biological Chemistry*.[2] Authored by Donald D. Van Slyke and James Maffett Neill, The Rockefeller Institute for Medical Research, New York, it describes a method for extracting and mea-

Table 1: Bibliography of the second 100 most-cited papers from the *SCI*®, 1945-1988. Papers are arranged alphabetically. A = 1945-1988 citations. B = 1945-1988 rank. C = average number of annual citations. D = 1988 citations. An asterisk (*) indicates that the paper was the subject of a *Citation Classic*® commentary. The issue, year, and edition of the commentary follow the bibliographic reference.

A	B	C	D	Bibliographic Data
2,887	119	78	74	***Abell L L, Levy B B, Brodie B B & Kendall F E.** A simplified method for the estimation of total cholesterol in serum and demonstration of its specificity. *J. Biol. Chem.* 195:357-66, 1952. (34/79/LS)
2,393	177	58	53	***Ahlquist R P.** A study of the adrenotropic receptors. *Amer. J. Physiol.* 153:586-600, 1948. (45/78)
3,148	102	131	82	**Andrews P.** The gel-filtration behaviour of proteins related to their molecular weights over a wide range. *Biochem. J.* 96:595-606, 1965.
2,493	167	86	74	***Anton A H & Sayre D F.** A study of the factors affecting the aluminum oxidetrihydroxyindole procedure for the analysis of catecholamines. *J. Pharmacol. Exp. Ther.* 138:360-75, 1962. (34/77)
2,264	198	75	248	**Arunlakshana O & Schild H O.** Some quantitative uses of drug antagonists. *Brit. J. Pharmacol.* 14:48-58, 1959.
3,076	106	96	163	**Bardeen J, Cooper L N & Schrieffer J R.** Theory of superconductivity. *Phys. Rev.* 108:1175-204, 1957.
2,776	132	121	130	***Bauer A W, Kirby W M M, Sherris J C & Turck M.** Antibiotic susceptibility testing by a standardized single disk method. *Amer. J. Clin. Pathol.* 45:493-501, 1966. (32/85/LS)
2,282	196	761	1,443	**Bednorz J G & Müller K A.** Possible high T_c superconductivity in the Ba-La-Cu-O system. *Z. Phys. B—Condens. Matter* 64:189-93, 1986.
2,970	113	248	425	**Benton W D & Davis R W.** Screening λgt recombinant clones by hybridization to single plaques *in situ*. *Science* 196:180-2, 1977.
2,499	166	500	727	***Berridge M J & Irvine R F.** Inositol trisphosphate, a novel second messenger in cellular signal transduction. *Nature* 312:315-21, 1984. (31/88/LS; 31/88/CM)
2,549	157	127	166	***Berry M N & Friend D S.** High-yield preparation of isolated rat liver parenchymal cells. *J. Cell Biol.* 43:506-20, 1969. (3/84/LS)
2,764	135	67	81	***Bloembergen N, Purcell E M & Pound R V.** Relaxation effects in nuclear magnetic resonance absorption. *Phys. Rev.* 73:679-712, 1948. (18/77)
3,134	104	261	273	**Bolivar F, Rodriguez R L, Greene P J, Betlach M C, Heyneker H L, Boyer H W, Crosa J H & Fakow S.** Construction and characterization of new cloning vehicles. II. A multipurpose cloning system. *Gene* 2:95-113, 1977.
2,447	172	91	150	***Born G V R.** Aggregation of blood platelets by adenosine diphosphate and its reversal. *Nature* 194:927-9, 1962. (37/77)
2,981	112	68	103	***Brunauer S, Emmett P H & Teller E.** Adsorption of gases in multimolecular layers. *J. Amer. Chem. Soc.* 60:309-21, 1938. (35/77)
2,737	136	342	615	**Burnette W N.** "Western blotting": electrophoretic transfer of proteins from sodium dodecyl sulfate-polyacrylamide gels to unmodified nitrocellulose and radiographic detection with antibody and radioiodinated protein A. *Anal. Biochem.* 112:195-203, 1981.
2,264	198	69	46	***Chance B & Williams G R.** The respiratory chain and oxidative phosphorylation. *Advan. Enzymol. Relat. Areas Mol.* 17:65-134, 1956. (49/83/LS)
2,871	122	65	129	***Chandrasekhar S.** Stochastic problems in physics and astronomy. *Rev. Mod. Phys.* 15:1-89, 1943. (47/89/ET&AS; 47/89/PC&ES)
2,377	181	91	105	**Crestfield A M, Moore S & Stein W H.** The preparation and enzymatic hydrolysis of reduced and S-carboxymethylated proteins. *J. Biol. Chem.* 238:622-7, 1963.
2,775	133	116	79	**Cromer D T.** Anomalous dispersion corrections computed from self-consistent field relativistic Dirac-Slater wave functions. *Acta Crystallogr.* 18:17-23, 1965.
2,691	141	142	75	***Cuatrecasas P.** Protein purification by affinity chromatography. *J. Biol. Chem.* 245:3059-65, 1970. (22/80/LS)
2,657	144	70	43	**Davis B D & Mingioli E S.** Mutants of *Escherichia coli* requiring methionine or vitamin B_{12}. *J. Bacteriol.* 60:17-28, 1950.
3,055	109	133	202	***Denhardt D T.** A membrane-filter technique for the detection of complementary DNA. *Biochem. Biophys. Res. Commun.* 23:641-6, 1966. (43/82/LS)
2,353	185	56	25	**Dische Z.** A new specific color reaction of hexuronic acids. *J. Biol. Chem.* 167:189-98, 1947.

A	B	C	D	Bibliographic Data
2,798	128	77	104	**Dixon M.** The determination of enzyme inhibitor constants. *Biochem. J.* 55:170-1, 1953.
2,915	116	112	135	**Dodge J T, Mitchell C & Hanahan D J.** The preparation and chemical characteristics of hemoglobin-free ghosts of human erythrocytes. *Arch. Biochem. Biophys.* 100:119-30, 1963.
2,326	187	80	62	**Dole V P & Meinertz H.** Microdetermination of long-chain fatty acids in plasma and tissues. *J. Biol. Chem.* 235:2595-9, 1960.
2,367	182	88	58	**Falck B, Hillarp N-Å, Thieme G & Torp A.** Fluorescence of catechol amines and related compounds condensed with formaldehyde. *J. Histochem. Cytochem.* 10:348-54, 1962.
2,790	129	164	152	***Feighner J P, Robins E, Guze S B, Woodruff R A, Winokur G & Munoz R.** Diagnostic criteria for use in psychiatric research. *Arch. Gen. Psychiat.* 26:57-63, 1972. (43/89/S&BS)
2,737	136	62	14	***Friedemann T E & Haugen G E.** Pyruvic acid. II. The determination of keto acids in blood and urine. *J. Biol. Chem.* 147:415-42, 1943. (18/85/LS)
2,851	126	124	237	**Glowinski J & Iversen L L.** Regional studies of catecholamines in the rat brain. I. The disposition of [^{3}H] norepinephrine, [^{3}H] dopamine, and [^{3}H] dopa in various regions of the brain. *J. Neurochem.* 13:655-69, 1966.
2,642	146	147	548	***Graham F L & Van der Eb A J.** A new technique for the assay of infectivity of human adenovirus 5 DNA. *Virology* 52:456-67, 1973. (46/88/LS; 46/88/CM)
2,587	153	216	224	***Grunstein M & Hogness D S.** Colony hybridization: a method for the isolation of cloned DNAs that contain a specific gene. *Proc. Nat. Acad. Sci. USA* 72:3961-5, 1975. (19/86/LS)
2,736	138	137	121	***Haber E, Koerner T, Page L B, Kliman B & Purnode A.** Application of a radioimmunoassay for angiotensin I to the physiologic measurements of plasma renin activity in normal human subjects. *J. Clin. Endocrinol. Metab.* 29:1349-55, 1969. (12/80/CP)
3,180	101	45	70	***Hales C N & Randle P J.** Immunoassay of insulin with insulin-antibody precipitate. *Biochem. J.* 88:137-46, 1963. (49/80/LS)
2,291	193	207	108	***Hamberg M, Svensson J & Samuelsson B.** Thromboxanes: a new group of biologically active compounds derived from prostaglandin endoperoxides. *Proc. Nat. Acad. Sci. USA* 72:2994-8, 1975. (2/83/LS)
2,413	174	101	87	**Hamilton W C.** Significance tests on the crystallographic *R* factor. *Acta Crystallogr.* 18:502-10, 1965.
2,569	156	61	16	**Hanes C S & Isherwood F A.** Separation of the phosphoric esters on the filter paper chromatogram. *Nature* 164:1107-12, 1949.
2,599	152	137	204	**Hartree E F.** Determination of protein: a modification of the Lowry method that gives a linear photometric response. *Anal. Biochem.* 48:422-7, 1972.
2,788	131	139	154	**Hehre W J, Stewart R F & Pople J A.** Self-consistent molecular-orbital methods. I. Use of Gaussian expansions of Slater-type atomic orbitals. *J. Chem. Phys.* 51:2657-64, 1969.
2,539	158	106	115	**Herbert V, Lau K-S, Gottlieb C W & Bleicher S J.** Coated charcoal immunoassay of insulin. *J. Clin. Endocrinol. Metab.* 25:1375-84, 1965.
3,054	110	69	112	**Higgins G M & Anderson R M.** Experimental pathology of the liver. I. Restoration of the liver of the white rat following partial surgical removal. *Arch. Pathol.* 12:186-202, 1931.
2,518	163	114	165	***Hirt B.** Selective extraction of polyoma DNA from infected mouse cell cultures. *J. Mol. Biol.* 26:365-9, 1967. (33/81/LS)
2,946	115	113	135	***Hoffmann R.** An extended Hückel theory. I. Hydrocarbons. *J. Chem. Phys.* 39:1397-412, 1963. (19/89/ET&AS; 19/89/PC&ES)
2,640	148	330	747	**Hsu S-M, Raine L & Fanger H.** Use of avidin-biotin-peroxidase complex (ABC) in immunoperoxidase techniques: a comparison between ABC and unlabeled antibody (PAP) procedures. *J. Histochem. Cytochem.* 29:577-80, 1981.
2,517	164	87	99	***Hubel D H & Wiesel T N.** Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *J. Physiol.—London* 160:106-54, 1962. (19/85/LS)
2,424	173	173	92	***Hughes J, Smith T W, Kosterlitz H W, Fothergill L A, Morgan B A & Morris H R.** Identification of two related pentapeptides from the brain with potent opiate agonist activity. *Nature* 258:577-9, 1975. (38/82/LS)
2,602	151	108	167	***Huzinaga S.** Gaussian-type functions for polyatomic systems. I. *J. Chem Phys.* 42:1293-302, 1965. (17/80/PC&ES)
2,951	114	105	31	**Jacob F & Monod J.** Genetic regulatory mechanisms in the synthesis of proteins. *J. Mol. Biol.* 3:318-56, 1961.

A	B	C	D	Bibliographic Data
2,914	117	81	10	***Jaffé H H.** A reexamination of the Hammet equation. *Chem. Rev.* 53:191-261, 1953. (33/77)
2,769	134	107	86	***Jerne N K & Nordin A A.** Plaque formation in agar by single antibody-producing cells. *Science* 140:405, 1963. (35/81/LS)
2,479	169	56	58	**Job P.** Formation and stability of inorganic complexes in solution. *Ann. Chim.—Paris* 9:113-203, 1928.
2,529	160	79	50	**Karplus M.** Contact electron-spin coupling of nuclear magnetic moments. *J. Chem. Phys.* 30:11-5, 1959.
2,822	127	235	104	***Kessler S W.** Rapid isolation of antigens from cells with a staphylococcal protein A-antibody adsorbent: parameters of the interaction of antibody-antigen complexes with protein A. *J. Immunol.* 115:1617-24, 1975. (13/83/LS)
2,790	129	116	263	**Kohn W & Sham L J.** Self-consistent equations including exchange and correlation effects. *Phys. Rev.* 140:1133-8, 1965.
2,345	186	73	92	**Kubo R.** Statistical-mechanical theory of irreversible processes. I. General theory and simple applications to magnetic and conduction problems. *J. Phys. Soc. Jpn.* 12:570-86, 1957.
3,051	111	96	84	**Layne E.** Spectrophotometric and turbidimetric methods for measuring proteins. *Meth. Enzymology* 3:447-9, 1957.
2,584	154	81	285	***Mantel N & Haenszel W.** Statistical aspects of the analysis of data from retrospective studies of disease. *J. Nat. Cancer Inst.* 22:719-48, 1959. (26/81/LS)
2,287	195	163	98	**McCann J, Choi E, Yamasaki E & Ames B N.** Detection of carcinogens as mutagens in the *Salmonella*/microsome test: assay of 300 chemicals. *Proc. Nat. Acad. Sci. USA* 72:5135-9, 1975.
2,379	179	103	57	**McConahey P J & Dixon F J.** A method of trace iodination of proteins for immunologic studies. *Int. Arch. Allergy Appl. Immunol.* 29:185-9, 1966.
2,860	124	143	214	***McCord J M & Fridovich I.** Superoxide dismutase. *J. Biol. Chem.* 244:6049-55, 1969. (17/81/LS)
2,658	142	60	15	**Mejbaum W.** Über die Bestimmung kleiner Pentosemengen insbesondere in Derivaten der Adenylsäure (Estimation of small amounts of pentose especially in derivatives of adenylic acid). *Hoppe-Seylers Z. Physiol. Chem.* 258:117-20, 1939.
2,525	161	421	766	**Messing J.** New M13 vectors for cloning. *Meth. Enzymology* 101:20-78, 1983.
2,312	190	210	264	***Mesulam M-M.** Tetramethyl benzidine for horseradish peroxidase neurohistochemistry: a non-carcinogenic blue reaction-product with superior sensitivity for visualizing neural afferents and efferents. *J. Histochem. Cytochem.* 26:106-17, 1978. (29/88/LS; 29/88/CM)
2,324	188	106	59	**Mishell R I & Dutton R W.** Immunization of dissociated spleen cell cultures from normal mice. *J. Exp. Med.* 126:423-42, 1967.
2,868	123	110	100	**Moore S.** On the determination of cystine as cysteric acid. *J. Biol. Chem.* 238:235-7, 1963.
2,259	200	73	31	**Moore S, Spackman D H & Stein W H.** Chromatography of amino acids on sulfonated polystyrene resins. *Anal. Chem.* 30:1185-90, 1958.
2,404	175	69	48	**Moore S & Stein W H.** A modified ninhydrin reagent for the photometric determination of amino acids and related compounds. *J. Biol. Chem.* 211:907-13, 1954.
2,365	183	58	25	**Moore S & Stein W H.** Photometric ninhydrin method for use in the chromatography of amino acids. *J. Biol. Chem.* 176:367-88, 1948.
2,363	184	91	86	***Morgan C R & Lazarow A.** Immunoassay of insulin: two antibody system. *Diabetes* 12:115-26, 1963. (52/77)
2,573	155	76	104	***Mulliken R S.** Electronic population analysis on LCAO-MO molecular wave functions. I. *J. Chem. Phys.* 23:1833-40, 1955. (33/85/ET&AS; 33/85/PC&ES)
2,642	146	120	58	***Murphy B E P.** Some studies of the protein-binding of steriods and their application to the routine micro and ultramicro measurement of various steroids in body fluids by competitive protein-binding radioassay. *J. Clin. Endocrinol. Metab.* 27:973-90, 1967. (3/81/LS)
2,877	120	80	168	***Nash T.** The colorimetric estimation of formaldehyde by means of the Hantzsch reaction. *Biochem. J.* 55:416-21, 1953. (14/81/LS)
3,140	103	628	817	**Nishizuka Y.** The role of protein kinase C in cell surface signal transduction and tumour promotion. *Nature* 308:693-8, 1984.
3,057	108	99	88	**Ouchterlony O.** Diffusion-in-gel methods for immunological analysis. *Prog. Allergy* 5:1-78, 1958.

A	B	C	D	Bibliographic Data
2,282	196	114	68	***Panyim S & Chalkley R.** High resolution acrylamide gel electrophoresis of histones. *Arch. Biochem. Biophys.* 130:337-46, 1969. (33/81/LS)
2,308	191	56	9	**Partridge S M.** Filter-paper partition chromatography of sugars. I. General description and application to the qualitative analysis of sugars in apple juice, egg white, and foetal blood of sheep. *Biochem. J.* 42:238-50, 1948.
3,104	105	239	188	***Pelham H R B & Jackson R J.** An efficient mRNA-dependent translation system from reticulocyte lysates. *Eur. J. Biochem.* 67:247-56, 1976. (6/85/LS)
2,723	139	227	334	**Peto R, Pike M C, Armitage P, Breslow N E, Cox D R, Howard S V, Mantel N, McPherson K, Peto J & Smith P G.** Design and analysis of randomized clinical trials requiring prolonged observation of each patient. Part II. Analysis and examples. *Brit. J. Cancer* 35:1-39, 1977.
2,296	192	100	56	***Pople J A & Segal G A.** Approximate self-consistent molecular orbital theory. III. CNDO results for AB2 and AB3 systems. *J. Chem. Phys.* 44:3289-96, 1966. (38/89/ET&AS; 38/89/PC&ES)
2,400	176	80	46	**Porter R R.** The hydrolysis of rabbit-γ-globulin and antibodies with crystalline papain. *Biochem. J.* 73:119-27, 1959.
2,625	149	97	73	***Reisfeld R A, Lewis U J & Williams D E.** Disk electrophoresis of basic proteins and peptides on polyacrylamide gels. *Nature* 195:281-3, 1962. (6/81/LS)
2,385	178	75	65	***Reitman S & Frankel S.** A colorimetric method for the determination of serum glutamic oxalacetic and glutamic pyruvic transaminases. *Amer. J. Clin. Pathol.* 28:56-63, 1957. (10/79/CP)
2,873	121	115	135	***Rodbell M.** Metabolism of isolated fat cells. I. Effects of hormones on glucose metabolism and lipolysis. *J. Biol. Chem.* 239:375-80, 1964. (45/80/LS)
2,611	150	65	76	**Roothaan C C J.** New developments in molecular orbital theory. *Rev. Mod. Phys.* 23:69-89, 1951.
2,483	168	166	187	***Salomon Y, Londos C & Rodbell M.** A highly sensitive adenylate cyclase assay. *Anal. Biochem.* 58:541-8, 1974. (17/82/LS)
2,464	170	77	66	**Schneider W C.** Determination of nucleic acids in tissues by pentose analysis. *Meth. Enzymology* 3:680-4, 1957.
2,658	142	148	177	***Seabright M.** Letter to editor. (A rapid banding technique for human chromosomes.) *Lancet* 2:291-2, 1971. (14/81/LS)
2,522	162	126	141	***Shannon R D & Prewitt C T.** Effective ionic radii in oxides and fluorides. *Acta Crystallogr. B—Struct. Sci.* 25:925-46, 1969. (21/81/PC&ES)
3,072	107	90	20	**Smithies O.** Zone electrophoresis in starch gels: some variations in the serum proteins of normal human adults. *Biochem. J.* 61:629-41, 1955.
2,379	179	61	26	***Sperry W M & Webb M.** A revision of the Schoenheimer-Sperry method for cholesterol determination. *J. Biol. Chem.* 187:97-106, 1950. (22/83/LS)
2,654	145	204	447	**Still W C, Kahn M & Mitra A.** Rapid chromatographic technique for preparative separations with moderate resolution. *J. Org. Chem.* 43:2923-5, 1978.
2,313	189	96	7	**Studier F W.** Sedimentation studies of the size and shape of DNA. *J. Mol. Biol.* 11:373-90, 1965.
2,291	193	88	44	***Sweeley C C, Bentley R, Makita M & Wells W W.** Gas-liquid chromatography of trimethylsilyl derivatives of sugars and related substances. *J. Amer. Chem. Soc.* 85:2497-507, 1963. (43/77)
2,904	118	104	113	***Till J E & McCulloch E A.** A direct measurement of the radiation sensitivity of normal mouse bone marrow cells. *Radiat. Res.* 14:213-22, 1961. (43/79/LS)
2,533	159	58	7	**Van Slyke D D & Neill J M.** The determination of gases in blood and other solutions by vacuum extraction and manometric measurement. I. *J. Biol. Chem.* 61:523-73, 1924.
2,464	170	257	116	**Vogel H J & Bonner D M.** Acetylornithinase of *Escherichia coli*: partial purification and some properties. *J. Biol. Chem.* 218:97-106, 1956.
2,693	140	269	228	***Wahl G M, Stern M & Stark G R.** Efficient transfer of large DNA fragments from agarose gels to diazobenzyloxymethyl-paper and rapid hybridization by using dextran sulfate. *Proc. Nat. Acad. Sci. USA* 76:3683-7, 1979. (26/90/AB&ES; 26/90/LS)
2,858	125	102	147	***Wilkinson G N.** Statistical estimations in enzyme kinetics. *Biochem. J.* 80:324-36, 1961. (24/87/LS)
2,500	165	139	149	***Yam L T, Li C Y & Crosby W H.** Cytochemical identification of monocytes and granulocytes. *Amer. J. Clin. Pathol.* 55:283-90, 1971. (50/80/CP)

suring gases in blood and other solutions. Citations to the paper increased steadily from 28 in 1945. They peaked at 126 in 1962. Since then they have declined to seven in 1988.

Another article of this decade was published in 1928 in *Annales de Chimie*.[3] "Formation and stability of inorganic complexes in solution" by P. Job, University of Lyon, France, was cited 2,479 times. In contrast to the Van Slyke paper, its citation pattern indicates continuing use over time. Cited an average of about 56 times per year since 1945, the paper peaked as late as 1975 (106 citations) and remained highly cited in 1988 (58 citations). Figure 1 is a graph of annual citations to these papers.

Six papers were published in the 1980s and are easily identified in Table 1 by scanning column C—they are the only ones with more than 300 citations per year: Johannes G. Bednorz and Karl A. Müller, IBM Research Laboratories, Zurich, Switzerland (1986);[4] Michael J. Berridge, University of Cambridge, UK, and Robin F. Irvine, Agricultural and Food Research Council, Cambridge, UK (1984);[5] W. Neal Burnette, Fred Hutchinson Cancer Research Center, Seattle, Washington (1981);[6] Su-Ming Hsu and colleagues, Brown University, Providence, Rhode Island (1981);[7] Joachim Messing, University of California, Davis (1983);[8] and Yasutomi Nishizuka, Kobe University School of Medicine, Japan (1984).[9]

Figure 2 shows a graph of the annual citations to these papers. All were hot papers, that is, fast starters that accumulated at least 100 citations in the first two years. But the Bednorz/Müller paper on high-temperature superconductivity rises to phenomenal heights—almost 2,300 citations through 1988—in the 28-month period since it was published in September 1986 in *Zeitschrift für Physik B—Condensed Matter*. It was cited 922 times in 1989 and 149 times in the first three months of 1990. The team won the 1987 Nobel Prize in physics.[10]

The two papers with the next steepest citation slopes are both on cell signal transduction and were published in 1984 in *Nature*. These and other high impact articles on this subject were highlighted in our study of the most-cited 1984 life-sciences articles.[11] Nishizuka and Berridge shared the 1989 Lasker Award for basic research with Alfred G. Gilman, University of Texas Southwestern Medical Center, Dallas, in recognition of their landmark work on cellular communication. Edwin G. Krebs, Howard Hughes Medical Institute and the University of Washington School of Medicine, Seattle, also shared the prize for his work on cellular metabolism.

Figure 1: Annual distribution of citations by year, 1945-1988 *SCI*®, to the two papers published in the 1920s in this study. See bibliography for full references.

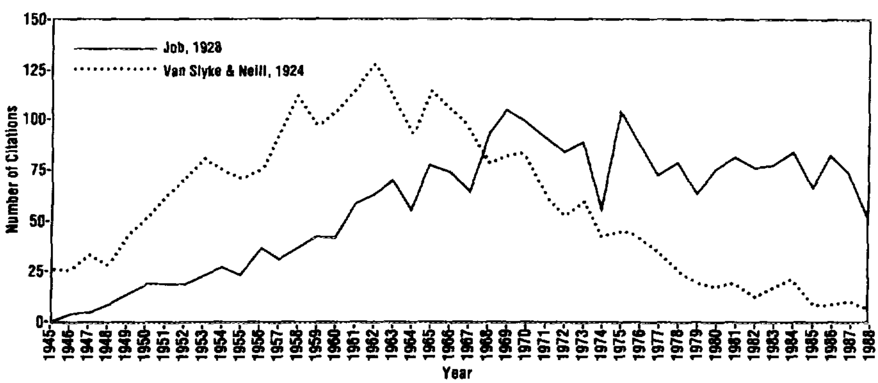


Figure 2: Annual distribution of citations by age of publication, 1945-1988 *SCI*®, for the six papers published in the 1980s in this study. Year zero represents the year each paper was published, and citation growth is measured year-by-year through 1988. See bibliography for full references.

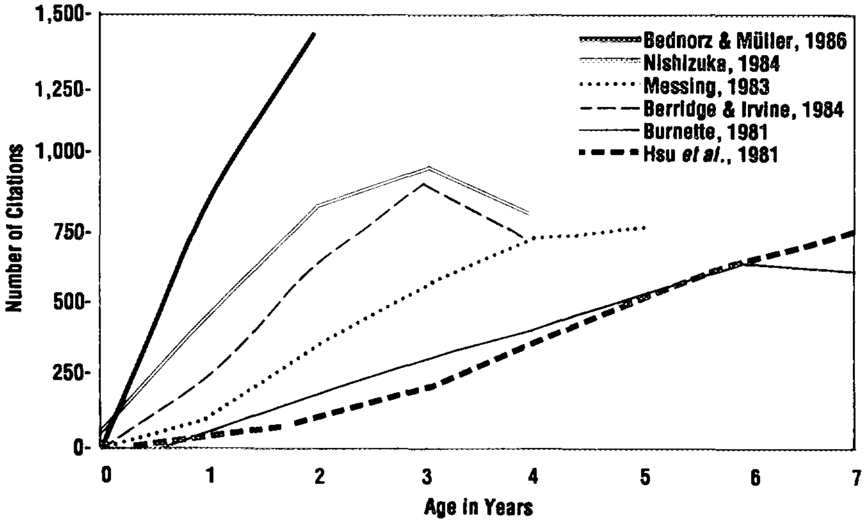


Table 2 provides details on the chronological distribution of the papers in this essay, showing number of papers by decade, total citations, average citations per year, and average 1988 citations. The data in parentheses are cumulated for the *SCI* Top 200 and will be updated with each successive essay in the series.

Where Are They Now?

It is interesting to note that all of the 1980s papers have been identified in previous studies of hot articles. This may seem to be an obvious and expected result. But it is not likely to hold as we move further down the list of all-time *Citation Classics.*

For example, of the 103 1977 life-sciences papers most cited in 1977 and 1978,[12] 36 still rank among the top 100 cited from 1977 through 1988. The others were displaced by papers that started out slower but built up enough citation momentum to overtake them. These fluctuations are simply a reflection of the complex dynamics of research-front movements. As the series continues and the sample of papers increases, we'll look back at annual hot article surveys of the 1980s and 1970s and keep track of where the papers now rank.

Physics Weighs In

Only one physics journal, *Physical Review Letters*, appeared in Part 1, and it published the only physics paper ranked among the *SCI* Top 100. Four more physics journals are represented in the bibliography, and they published seven papers: *Physical Review* with three, *Reviews of Modern Physics* with two, and the *Journal of the Physical Society of Japan* and *Zeitschrift für Physik B—Condensed Matter* with one each.

As we've often explained, citation patterns vary between and within fields. This is illustrated in Table 3, which shows the field distribution of 1984 papers in the *SCI* and citation data over the five-year period from 1984 to 1988. The life-sciences journal literature is the largest with about 385,000 articles (56 percent of all *SCI* articles). Its total five-year impact of 4.45 is intermediate

Table 2: Chronological distribution of the second 100 most-cited papers from the *SCI*®, 1945-1988. Data in parentheses are cumulated through the top 200 most-cited papers identified to date.

Decade	Number of Papers	Total Cites	Average Citations Per Year	Average 1988 Cites
1920s	2 (3)	5,012 (22,259)	57 (157)	33 (184)
1930s	3 (7)	8,693 (33,857)	103 (110)	77 (87)
1940s	8 (17)	20,360 (80,606)	123 (142)	44 (146)
1950s	23 (47)	60,314 (397,966)	86 (245)	89 (183)
1960s	39 (73)	103,228 (325,753)	108 (186)	111 (171)
1970s	19 (45)	50,364 (278,793)	194 (427)	236 (721)
1980s	6 (8)	15,823 (29,868)	471 (559)	853 (965)
TOTAL	100 (200)	263,794 (1,169,102)	152 (254)	206 (351)

between that of physics (5.06), which includes astronomy and astrophysics, and chemistry (4.07). Although the engineering literature ranks second in number of articles (approximately 80,000, or 12 percent of 1984 *SCI* articles), the average paper received just 1.08 citations from 1984 to 1988, the lowest impact of *SCI* fields.

The size of the literature, average number of references cited per article, time lag between manuscript submission and publication, median age of cited items, and many other factors shape these differences between fields. The life sciences typically dominate lists of highly cited articles. Chemistry, physics, the geosciences, and other disciplines with comparatively lower citations for superstar papers begin to appear in the lower rankings. As this series progresses, the fields represented by the all-time *Citation Classics* will include more papers from these and other disciplines.

"Late Bloomers"

In Part 1 we suggested that ISI's file of about 500,000 papers and books cited at least 50 times from 1945 to 1988 would be fertile ground for uncovering possible examples of "delayed recognition"—high impact papers that were initially overlooked and only later appreciated. Stephen G. Brush, Institute for Physical Science and Technology, University of Maryland, College Park, recently reviewed the most-cited physical-sciences papers in the newly published 1945-1954 *SCI* cumulation.[13] He described similar examples of what he called "late bloomers," such as a 1943 *Reviews of Modern Physics* paper on stochastic problems in astrophysics by 1983 Nobel physics laureate Subrahmanyan Chandrasekhar, University of Chicago, Illinois.[14]

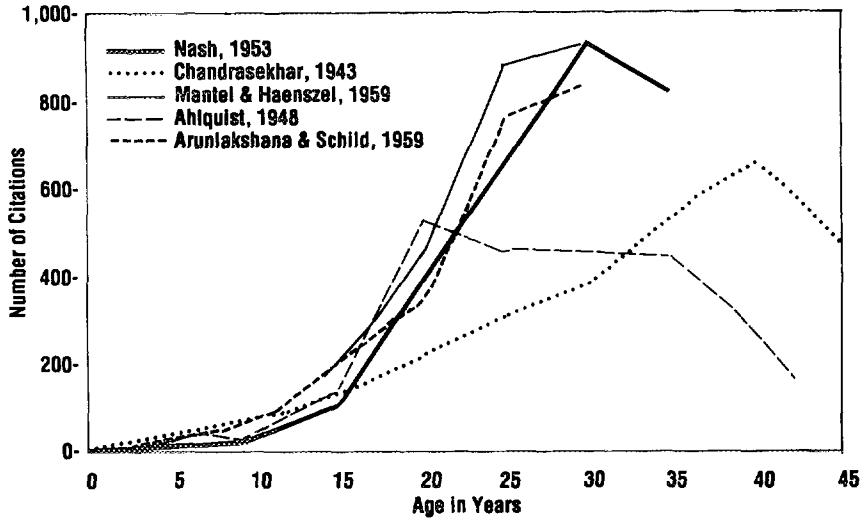
Figure 3 is a graph of annual citations to this paper and four others whose citation patterns might also qualify them as examples of delayed recognition or "late bloomers": Raymond P. Ahlquist, Medical College of Georgia, Augusta (1948);[15] O. Arunlakshana and H.O. Schild, University College, London, UK (1959);[16] Nathan Mantel and William Haenszel, National Cancer Institute, Bethesda, Maryland (1959);[17] and T. Nash, Public Health Laboratory Service, London (1953).[18]

In a 1978 *Citation Classic* commentary, Ahlquist acknowledged that his paper was

Table 3: Field distribution of source items indexed in the 1984 ISI® databases, and citations, 1984-1988.

Field	1984 Articles	1984-1988 Citations	Five-Year Impact
Life Sciences	384,781	1,712,378	4.45
Engineering	80,093	86,796	1.08
Physics	72,742	368,171	5.06
Chemistry	68,216	277,308	4.07
Geosciences	29,462	104,995	3.56
Multidisciplinary	23,128	197,736	8.55
Mathematics	17,993	26,209	1.46
Technology	15,519	33,296	2.15
TOTAL	691,934	2,806,889	4.06

Figure 3: Annual distribution of citations by age of publication, 1945-1988 *SCI*®, for so-called late bloomer articles. Year zero represents the year each paper was published, and citation growth is measured year-by-year through 1988. See bibliography for full references.



initially resisted and ignored because the concept of alpha and beta receptors it discussed "did not fit with ideas developed since 1890 on the actions of epinephrine."[19] Mantel explained in his 1981 commentary that the increased citation of his paper was the consequence of the proliferation of observational studies and clinical trials as well as "growing awareness of the statistical community" of the paper.[20] Nash did not specifically discuss citation trends in his 1981 commentary,[21] while Chandrasekhar stated generally that "it's very difficult to describe my work.... Usually [it] has become appreciated only after some length of time."[22]

Nobel Laureate Authors of the All-Time *Citation Classics*

Including Bednorz, Chandrasekhar, and Müller, there are 19 Nobel laureates listed on 15 papers in Table 1. The physics prizewinners are John Bardeen, University of Illinois, Urbana; Leon N. Cooper, Brown University; John Robert Schrieffer, University of California, Santa Barbara; and Nicolaas Bloembergen and Edward M. Purcell, Harvard University, Cambridge, Massachusetts.

The Nobel chemists listed are Roald Hoffmann, Cornell University, Ithaca, New York; Stanford Moore and William H. Stein, The Rockefeller Institute; and Robert S. Mulliken, University of Chicago. Prizewinners in medicine are David H. Hubel, Harvard, and Torsten N. Wiesel, The Rockefeller University, New York; François Jacob and Jacques L. Monod, Pasteur Institute, Paris, France; Niels Kaj Jerne, University of Pittsburgh Medical School, Pennsylvania; Rodney R. Porter, National Institute for Medical Research, London; and Bengt I. Samuelsson, Karolinska Institute, Stockholm, Sweden.

Table 4 lists the Nobelists who have appeared on the *SCI* Top 200 papers, showing the year and field of the prize, and number of papers in the present and cumulated list. This information will be updated and cumulated in future essays in this series.

Two papers by Nobelists show a "twin-peak" citation pattern that may indicate resurgent interest in the subjects discussed:

Table 4: Nobel Prize winners appearing in the 200 most-cited papers, *SCI*®, 1945-1988. A = name. B = year and prize. C = number of papers in which the Nobelist appears in the second 100 top-cited papers from the *SCI*®, 1945-1988. D = total number of papers in which the Nobelist appears in the 200 top-cited papers from the *SCI*, 1945-1988.

A	B	C	D
John Bardeen	1956/Physics	1	1
Johannes G. Bednorz	1987/Physics	1	1
Nicolaas Bloembergen	1981/Physics	1	1
Subrahmanyan Chandrasekhar	1983/Physics	1	1
Leon N. Cooper	1972/Physics	1	1
Roald Hoffmann	1981/Chemistry	1	1
David H. Hubel	1981/Physiology or Medicine	1	1
François Jacob	1965/Physiology or Medicine	1	1
Niels K. Jerne	1984/Physiology or Medicine	1	1
Jacques L. Monod	1965/Physiology or Medicine	1	2
Stanford Moore	1972/Chemistry	5	6
Karl A. Müller	1987/Physics	1	1
Robert S. Mulliken	1966/Chemistry	1	1
Rodney R. Porter	1972/Physiology or Medicine	1	1
Edward M. Purcell	1952/Physics	1	1
Bengt I. Samuelsson	1982/Physiology or Medicine	1	1
John Robert Schrieffer	1972/Physics	1	1
William H. Stein	1972/Chemistry	4	5
Torsten N. Wiesel	1981/Physiology or Medicine	1	1

Bardeen *et al.*'s 1957 *Physical Review* paper on superconductivity[23] and Hoffmann's 1963 *Journal of Chemical Physics* paper on an extended Hückel theory for hydrocarbons.[24] Figure 4 is a graph of the annual citations to these papers. Both papers are apparently reaching a "second wind" in citations, but the reasons for this in each case can only be determined by examining the citing papers. The trend for the Bardeen *et al.* paper is likely due to the discovery of new high-temperature superconducting materials in 1987. These advances dominated our list of the 100 1987 physical-sciences papers most cited in 1987 and 1988.[25]

We asked Hoffmann whether he could explain the renewed interest in his 1963 paper. He noted that the extended Hückel theory

Figure 4: Annual distribution of citations by age of publication, 1945-1988 *SCI*®, for two putative second-wind papers. Year zero represents the year each paper was published, and citation growth is measured year-by-year through 1988. See bibliography for full references.

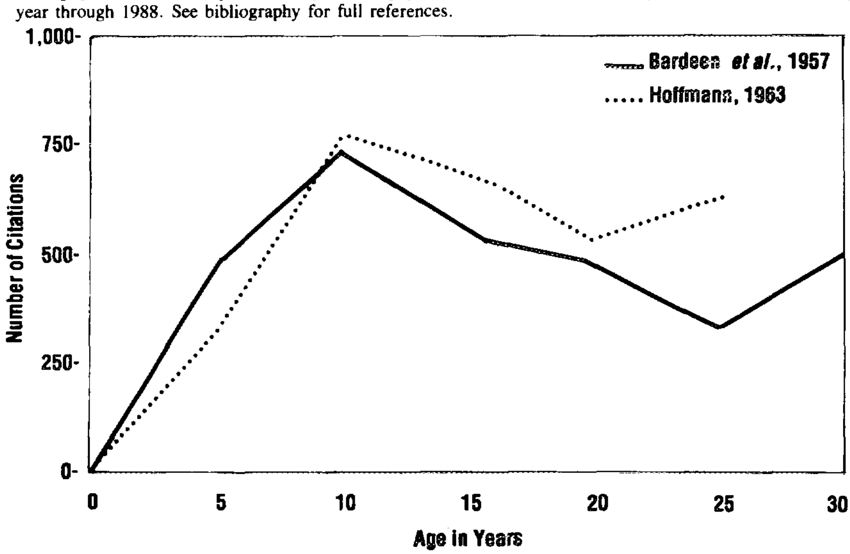


Table 5: The journals that published the second 100 most-cited *SCI*® papers. A = title, with first year of publication in parentheses. B = number of most-cited articles.

A	B
J. Biol. Chem. (1905)	14
Biochem. J. (1906)	8
J. Chem. Phys. (1931)	6
Nature (1869)	5
Proc. Nat. Acad. Sci. USA (1915)	4
Acta Crystallogr. (1948)	3
Amer. J. Clin. Pathol. (1931)	3
Anal. Biochem. (1960)	3
J. Clin. Endocrinol. Metab. (1941)	3
J. Histochem. Cytochem. (1953)	3
J. Mol. Biol. (1959)	3
Meth. Enzymology (1955)	3
Phys. Rev. (1893)	3
Arch. Biochem. Biophys. (1942)	2
J. Amer. Chem. Soc. (1879)	2
Rev. Mod. Phys. (1930)	2
Science (1880)	2
Advan. Enzymol. Relat. Areas Mol. (1967)	1
Amer. J. Physiol. (1898)	1
Anal. Chem. (1929)	1
Ann. Chim.—Paris (1789)	1
Arch. Gen. Psychiat. (1959)	1
Arch. Pathol. (1926)	1
Biochem. Biophys. Res. Commun. (1959)	1
Brit. J. Cancer (1947)	1
Brit. J. Pharmacol. (1946)	1
Chem. Rev. (1924)	1
Diabetes (1952)	1
Eur. J. Biochem. (1967)	1
Gene (1977)	1
Hoppe-Seylers Z. Physiol. Chem. (1877)	1
Int. Arch. Allergy Appl. Immunol. (1950)	1
J. Bacteriol. (1916)	1
J. Cell Biol. (1962)	1
J. Exp. Med. (1896)	1
J. Immunol. (1916)	1
J. Lab. Clin. Med. (1915)	1
J. Nat. Cancer Inst. (1940)	1
J. Neurochem. (1956)	1
J. Org. Chem. (1936)	1
J. Pharmacol. Exp. Ther. (1909)	1
J. Phys. Soc. Jpn. (1946)	1
J. Physiol.—London (1878)	1
Lancet (1823)	1
Prog. Allergy (1939)	1
Radiat. Res. (1954)	1
Virology (1955)	1
Z. Phys. B—Condensed Matter	1

was initially very useful in organic chemistry and, during the mid-1970s, was also being applied to inorganic molecules. In addition, during the early 1980s, the theory found application in the subfields of solid-state and surface chemistry. Hoffmann suggests that the paper's citation record might therefore reflect its exposure to these new groups of users.[26]

Prolific High Impact Authors

Five authors are represented more than once. Moore is the most prolific with five papers among the second 100 all-time *Citation Classics*. He was first author on four, three of which were coauthored with Stein, and one also with Darrel H. Spackman, The Rockefeller Institute. (The three also coauthored one of the *SCI* Top 100 papers reviewed in Part 1.) In addition, Moore and Stein appear on a paper with A.M. Crestfield, The Rockefeller Institute, as first author.

The following authors each have two papers in Table 1: Mantel; John A. Pople, Carnegie-Mellon University, Pittsburgh; and Martin Rodbell, National Institute of Arthritic and Metabolic Disease, Bethesda.

The authors who have appeared more than once through the *SCI* Top 200 are Moore (six papers); Stein (five); Don T. Cromer, University of California, Los Alamos Scientific Laboratory, New Mexico (four); and Bruce N. Ames, University of California, Berkeley (three). The following authors had two papers each: Patrick Andrews, National Institute for Research in Dairying, Reading, UK; David R. Cox, Imperial College of Science and Technology, London; Vincent P. Dole, The Rockefeller Institute; Joyce McCann, University of California, Berke-

Table 6: Journals that published five or more of the top 200 most-cited *SCI*® papers, 1945-1988. A = title, with first year of publication in parentheses. B = number of most-cited papers.

A	B
J. Biol. Chem. (1905)	31
Biochem. J. (1906)	12
Nature (1869)	10
Proc. Nat. Acad. Sci. USA (1915)	10
J. Chem. Phys. (1931)	8
Anal. Biochem. (1960)	7
J. Mol. Biol. (1959)	7
Acta Crystallogr. (1948)	6
J. Cell Biol. (1962)	5
J. Histochem. Cytochem. (1953)	5

ley; Monod; Walter C. Schneider, National Institutes of Health, Bethesda; Spackman; Robert F. Stewart, University of Washington; and Edith Yamasaki, University of California, Berkeley.

Journals of the *SCI* Top 200

The *Journal of Biological Chemistry* again leads all others in publishing the most all-time *Citation Classics*. Table 5 shows that it accounts for 14 papers in this study, bringing its total through the *SCI* Top 200 to 31. The *Biochemistry Journal* is second, with 8 articles in this study and 12 total to date. Table 6 shows all journals that have published at least 5 papers ranked among the *SCI* Top 200. The *Proceedings of the National Academy of Sciences of the USA* shares third place with *Nature*, and they are followed by the *Journal of Chemical Physics*, *Analytical Biochemistry*, and the *Journal of Molecular Biology*.

Editors should note that this series of essays can be used to create bibliographies of the most-cited articles from their own and other journals. We've already covered the 31 most-cited articles from the *Journal of Biological Chemistry*, and in this essay we've identified the most-cited articles from 29 journals appearing on the list for the first time. For any journal or group of journals, ISI can identify articles that were cited at least 50 times from 1945 to 1988 and track each article's citations on a year-by-year basis.

The Next 100

In the near future, we will continue this series of essays by identifying another 100 all-time *Citation Classics*—those ranked number 201-300 in our file of papers most cited from 1945 to 1988. In addition to highlighting specific papers and citation patterns of interest in that group, we will cumulate all data through the *SCI* Top 300 on chronological distributions, Nobel laureate authors, and journals.

We welcome comments from *CC* readers on the most-cited papers of all time that have been identified to date. Readers interested in previewing the upcoming list of the third 100 papers should write to Al Welljams-Dorof, ISI's director of editorial services.

* * * * *

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