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JACOB J. BIKERMAN, FRICTION AND ADHESION

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Professor J. J. Bikerman was born in Odessa in south-west U.S.S.R. (in the Province of Moldavia, near the border with Romania) and was educated in St. Petersburg, Berlin, Manchester and Cambridge. He died in Cleveland on June 11, 1978.

The topic on which Dr. Bikerman spoke most frequently was adhesion but he also had some very interesting views on friction. His was a minority view but a very informed view and worth hearing. Unfortunately, with his passing we must proceed without benefit of his fervor and imagination but now is a good time to present a historical perspective of Dr. Bikerman's ideas. In order to do so it is helpful first to summarize his personal history. His journey from Odessa to Cleveland is a fascinating story in itself, a story that may be found partly in the dual autobiography of Joseph Bikerman and his son Jacob J. Bikerman [1].

Dr. Bikerman could trace his clan to the early 1800s in the region immediately adjacent to the north shore of the Black Sea. The Bikerman family became progressively poorer through the 1800s until Joseph Bikerman reversed the fortunes of the family. Part of this increasing poverty was because of the place allotted to Jews in Russia of that era but part was due to the tendency of Jacob's ancestors to pursue intellectual interests rather than money. Joseph was a direct beneficiary of the intellectually rich environment of the family. He became a political journalist and writer and achieved some prominence in the tumultuous times leading to the victory of the Bolsheviks in Russia.

Jacob Bikerman was born in Odessa in 1898, the same year that the Soviet Democratic Labor Party was formed. It was the Bolshevik or majority faction of this party which was to achieve prominence under the direction of V. I. Lenin but which also fomented revolution and disorder in the nation. The plight of the Jews was a separate issue and Jacob learned this fact at the tender age of seven. A pogrom occurred within a few blocks of his home (a pogrom is a violent action against Jews by marauders operating without interference by authorities). In the same year (1905) the Bikerman family moved to St. Petersburg (now Leningrad since 1924) where Joseph was connected with a number of newspapers operated mostly by Jews and having as their major banner the removal of the Czars from power. Joseph had no intention of supporting the Bolsheviks, but in being revolutionary he appeared to walk a parallel path with the more extreme Bolsheviks. There were considerable risks in being revolutionary as Joseph learned by being imprisoned for several short periods. However, the oppression against Jews and moderate revolutionaries came slowly enough so that the family learned circumspect external behavior and methods of survival.

The Russian educational system proceeded without major disruption long enough for Jacob to receive a good education. He read widely and was brought into contact with intellectuals of a wide range of thought. The economic state of the country deteriorated slowly from about 1900 until World War I when gross disorder began. By the end of the war in 1918 there was widespread shortage of food and municipal services. The intense Bolshevik revolution after the war caused more severe disruptions and interrupted Jacob's university years briefly. Jacob studied physical chemistry and did experimental research in a time of serious shortages of fuel, electricity, water and scientific supplies. Imagine the persistence required to work in a laboratory where water freezes and the one light bulb is your own and it is frequently dark. In the summer of 1921 he completed his studies but did not receive a degree because academic titles had been abolished 2 years earlier. Thus he was "rewarded with just two sheets of low quality paper, on one of which it was typed in a pale ink that I completed all required courses in the Biology Department . . .".

In the years 1917 - 1922, the revolution took a heavy toll in lives as well as material well-being. Large fractions of the population in some regions starved to death. Millions were killed by the Bolsheviks for a variety of reasons. Dr. Bikerman states a motto of the time: "I consider myself shot dead — anything less final is pure gain." The Bikermans frequently heard of the disappearance or demise of neighbors, friends or relatives but their immediate family was not touched. Dr. Bikerman recounts many events that could have ended in personal disaster but he survived. Upon reflection he states: "Only repeat winners, favorites of fate, are still alive and reminiscing."

In 1922 the family decided to leave the country if possible. The manner by which this was accomplished indicates the influence that Joseph had in revolutionary circles. Jacob's oldest brother had been drafted into the Red (Bolshevik dominated) army and was living in some peril in central Russia. Joseph Bikerman interceded through a lieutenant of Trotsky to have his eldest son transferred to Moscow and granted leave to spend time with the family. Using similar high connections and many false documents, the family travelled to Minsk presumably to spend the Christmas holiday here. In Minsk they acquired authorization as repatriated Polish refugees to travel to Novo-vileiki, Poland. Joseph, his wife and two sons posed as the Berman family which required considerable rehearsal to avoid slip-ups. Thousands of others were also attempting to escape Russia and the transportation system was hopelessly crowded. Real perils existed in the form of very cold weather, lice that carried typhus, and frequent roundups in the constant search for contraband and escaping military personnel. Once on a train it took 35 tense hours to go the 36 miles from Minsk to the Polish border. When in Poland the family made their way to Warsaw where through the Jewish community they were able to obtain more forged documents for entry into Germany.

In Berlin, Jacob applied to the University for further study and employment. For income he wrote abstracts for the German Chemisches Zentralblatt and he studied under the physical chemist, Professor H. Freundlich. Political tumult in Germany began at about the time of the arrival of the Bikermans. The Nazis were pressing for a prominent role in the nation and part of their dogma was the defamation of Jews. Employment opportunities for the Jews diminished with time and personal safety did as well. In spite of the turmoil Jacob did not ignore the personal side of his life. In 1933 he married a Jewess who was also born in Odessa. In 1935, after the death of Joseph, Jacob decided to leave Germany. In 1936 he and his wife went to England where Jacob worked with Professor Michael Polanyi at the University of Manchester. A year later he entered the laboratory of Colloid Science at Cambridge University and began experiments under the direction of Professor E. K. Rideal for the purpose of finishing the requirements for the doctor's degree.

It would seem that the peace and security of England would have calmed the spirit of Bikerman, but it was not to be. In his autobiography he speaks of distress in the area of personal interactions with professional colleagues and of the unwillingness of the English to heed his advice on the advancing menance of the Nazis. Again he felt under oppression. In his intellectual discourse he was pitted against Professor Rideal, Dr. Irving Langmuir and others, but he also remained active in research. It was in this climate that he heard two lectures given by students of Professor F. P. Bowden (1903 - 1968). These students, L. Leben and D. Tabor, "reported on their work in friction and adhesion. Neither of these branches of science was of particular interest to me before, but the adhesion theory of friction, as presented by Leben and Tabor, at once struck me as incorrect. Fortunately I was free to read or do whatever I liked, independently of the value of this activity to the study of "built-up" films for which I was paid. I purused the essential literature on friction from Coulomb (1809) to W. B. Hardy (1922) and became convinced that my first impression was correct and the Hardy–Bowden theory wrong."

"Several simple experiments confirmed my understanding of the phenomenon which was identical with that of Coulomb. The article reporting my results was published as a joint paper with Rideal . . . [2]. My views on the mechanisms of friction have not changed since 1938, but very few scientists agree with me."

In order to appreciate Dr. Bikerman's views on friction it would be useful to present a short history of the study of friction. A great number of scientists and philosophers have written on the subject. In the early years friction was referred to as the resistance of one body to sliding over another. The origin of the word friction is not known. Many of the concepts are lost or were never adequately followed but accounts of early attitudes are given by Professor D. Dowson [3] in various installments. It is not possible to name the first author of formal thinking on the subject but Leonardo Da-Vinci (1452 - 1519) is given credit for some early insights. He found that for many substances the frictional sliding resistance is proportional to one-third the weight or applied load. Euler, a Swiss theologian, physicist and physiologist, who followed Bernoulli as Professor of Physics at St. Petersburg in 1707 said that friction was due to arrays of little hypothetical hills on sliding surfaces. A force is required to climb the hills and no force is required to go down the other side of the hills.

Coulomb (1736 - 1806), a French physicist–engineer, picked up this theme and stated that friction must be due to interlocking of asperities since actual surfaces are frictionless. He was well aware of attractive forces between surfaces because of the discussions of that time of gravitation and electrostatics. In fact Coulomb measured electrostatic forces and found that they followed the inverse square law (force is inversely related to the square of distance of separation) that Newton had guessed (1686) applied to gravitation. However, Coulomb discounted adhesion (cohesion) as a source of friction because friction is usually found to be independent of (apparent) area of contact. It is interesting to note that, whereas Coulomb was in error in his explanation, today "dry friction" is almost universally known as "Coulomb friction" particularly in mechanics and physics.

Two other names of the era of Coulomb should also be mentioned. The first is Amontons, a French engineer who wrote that the cause of friction is the collision of surface irregularities. Amontons is probably the most widely referenced author in academic papers on friction at least. Amontons' Laws of Friction state that the coefficient of friction is independent of load, speed and area of contact and that is still printed in physics textbooks of today. These laws were adequate for the materials and machines of the time but find limited value today. However, modern authors often use Amontons as a point of departure when promulgating their own views. The second, more obscure author is Leslie (1766 - 1832) an Englishman who may have strongly influenced Dr. Bikerman's thinking. Leslie stated that adhesion can have no effect in a direction parallel to the surface since adhesion is a force perpendicular to the surface. Rather friction must be due to the sinking of asperities.

Sir W. B. Hardy, a physical chemist at Cambridge, in a paper with A. K. Hardy [4] concluded that dry static friction is due to cohesion or seizing and not due to "inequalities" of surfaces. They showed that monomolecular films of liquid greatly reduce friction without diminishing surface roughness. Without the fluid film there is cohesion, but this cohesion is not felt in the normal direction. The authors explain that this is partly due to peeling but partly also because more alteration of polarization of solid surface "molecules" (glass) occurs during sliding than during normal separation.

The latter point was never confirmed but Dr. Bikerman rejected the idea of peeling immediately. In later years he expressed some doubts also about Hardy's hypothesis that adsorbed films of liquid become solid-like, such that "the film now has gained tenacity and lost fluidity". This conviction was obtained from experiments in glass sliding on glass where there was most definitely an interposing thin film. Both glass surfaces were damaged.

The paper by Hardy and Hardy is probably the pivotal paper from which two strong views developed and were debated for the next 50 years or so. A student of Sir W. B. Hardy, namely F. P. Bowden, pursued further research on friction and strongly favored the idea of cohesion as the chief cause of friction. In fact, the adhesion (substituted for cohesion) explanation of friction is most often attributed to Drs. Bowden and Tabor although there are conflicting claims to this honor. As usual, conflicting claims are supported by "proof" of prior publication of other ideas or results. However, it is easy to be mistaken in ideas and in the interpretation of research results, so full credit should not go to one who does not adequately convince others of his ideas. On the latter part alone, Bowden and Tabor are worthy of the honor accorded them. The adhesion theory was formulated in two papers [5, 6]. These were treatises on the inadequacy of the interlocking theory. The second paper advanced the idea that the force of friction is the product of the area of contact and the shear strength of the bond in that region, *i.e.* $F = AS_s$. To complete the model, the load was thought to be born by the tips of asperities, altogether comprising a total area of contact multiplied by the average pressure of contact, $W = AP_f$. The average pressure of contact was thought to be that for fully developed plastic flow such as under a hardness test identer thus the subscript in P_f. Altogether

$$\mu = F/W = AS_s/AP_f = S_s/P_f$$

Both S_s and P_f are properties of materials and the usual ratio S_s/P_f for ductile metals is between 0.17 and 0.2. Thus $\mu \approx 0.2$ and this is often found in practice for clean metals in air.

The early theory of Tabor was open to some criticism because it does not adequately explain variation in friction much lower than 0.2 or much greater than 0.2 and it does not explain the difference between static friction and kinetic friction. Bikerman never states whether or not this is his major difference with the theory of Tabor. Perhaps he regarded these equations as only a symptom and not the real disease.

His own views were stated in a paper by himself and E. K. Rideal [2] in which they show that friction force varies with applied load. Many others have shown the same but to Dr. Bikerman this proved that adhesion is not the cause of friction. He acknowledged that the area of contact increases with load but insisted that it does not decrease with a decrease in load. In essence this arises from his denial of peeling of bonded surfaces by elastic recovery. We have no record of Dr. Bikerman's reaction to later work on this subject, particularly to a paper by K. L. Johnson [7]. Peeling by elastic recovery had been envisioned certainly by Bikerman's time to occur in the following manner. The model of a surface in this case is often taken to be a sphere on a flat plate. When the sphere is resting on the plate there is very little contact between the sphere and the plate. With external loading upon the sphere, both the sphere and the flat plate deform so that the contact area between the two is increased. At this point, it is agreed, cohesion or seizing may be envisioned to occur over the entire contact area. Now as the external load is relaxed or relieved, most people believe that the sphere and the flat plate tend toward the original shape even though the contacting bodies were plastically deformed. Separation of the sphere from the flat plate would occur at the outer edges of contact first where, in section view, a sharp crack may be seen to exist. This sharp crack or high stress concentration, coupled with a high separating stress, will tend to tear apart the outer edges of contact between the sphere and the flat plate. As the load is further relieved the next ring of bonding or seizure is torn apart. This progressive tearing or peeling of the sphere from the flat plate occurs during unloading, leaving a very small contact region in place under the weight of the sphere alone. Dr. Bikerman was not convinced.

The same paper expressed some difficulties with the use of the term adhesion. He, with Leslie, defined adhesion as a force perpendicular to a surface and friction as the force parallel to the surface. Thus the adhesion theory of friction was a contradiction in terms to him. He clarified his own definitions of these terms in a later paper [8]. He describes an experiment in which a polymer strip is pressed against a metal surface at about 130 °C for 30 min. After cooling, the force needed to displace the strips tangentially along the metal surface was measured several times using a number of normal pressures applied upon the polymeric strip. In all cases, the force required to initiate sliding was 3×10^7 dyne. After the initiation of sliding, the force to continue sliding was of the order of 10^5 dyne and was found to be proportional to the applied normal load. The high force was attributed by Dr. Bikerman to adhesion and the lower forces to friction. Others would have defined the difference in terms of static and kinetic friction.

Dr. Bikerman's third area of dissent concerns the role of absorbed gas films. It must be admitted that many followers and defenders of the adhesion theory of friction dismiss the role of adsorbed gas films in a careless manner. Statements found in papers on lubrication often carry a comment as follows: "As the load on lubricated sliding bodies increases, the lubricant film collapses and asperity adhesion occurs." Interestingly, these statements are often made by authors in elastohydrodynamics who should know that the sudden disappearance of a thin film of fluid is not consistent with the continuity of matter. Bikerman argues that the absorbed gases do not disappear. If they disappear then metals would adhere and "if metals adhere so well then adhesives would never have been developed." Dr. Bikerman envisions the function of liquid adhesives to involve primarily a chemical combination with the adsorbed gas film, thus removing it as the weak element in the load-carrying interface. He reasons that since this film is not removed by chemical action in metal contact it must persist and frustrate any tendency of the metal interfaces to seize or adhere. Again, to Dr. Bikerman the absence of adhesion was proved when the upper slider is lifted from the lower by a use of a force no greater than the weight of the upper body.

Perhaps some of the difference between Dr. Bikerman and the Hardy–Bowden–Tabor school on the existence and effect of adsorbed films is derived from a difference in attitude on the properties of adsorbed gas films. Hardy and Hardy postulated the solid-like behavior of the gas film. In the 1974 paper, Bikerman expressed the opinion that "the adsorbed air films are so thin and so mobile that their deformation requires very little work compared with that spent on the deformation of the (substrate)." Again, "absorbed layers are not removed during sliding. Usually sliding is a very slow process compared with evaporation, condensation and tangential motion of absorbed molecules; thus these three processes are not markedly influenced by friction." It must be stated that in spite of the fine work on the contact between molecularly smooth surfaces upon which adsorbed monolayers exist, no final resolution of Dr. Bikerman's objection or comments on the adsorbed film has yet been published. Whatever the outcome of such work, the care with which conclusions will be reached will be strongly influenced by the care with which opposing arguments have been advanced over the years.

The vigor and ingenuity with which Dr. Bikerman debated his views was a delight to all who heard him. He evidently felt, however, very clearly the underdog. In his autobiography he goes on: "How was it possible that truth which is so obvious to me has not prevailed in 35 years? It seems to me that this is a good example of the importance of external circumstances in the history of Science. I had a very limited opportunity of doing experimental work and almost none of these experiments were on friction; thus I could only preach. Bowden's laboratory was one of the few which for many years was devoted almost exclusively to friction; thus his students could publish perhaps a score of experimental papers for every sermon of mine. Former students of Bowden now direct their own laboratories and continue the tradition of their teacher without any reference to the views of Coulomb whom many of them presumably never read. Thus the voice of the majority has drowned the small voice of a doubter."

Dr. Bikerman's views on friction have not prevailed but his spirit and accomplishments were undeniably of high order. Few have accomplished what he has and fewer still will have begun making these accomplishments in the face of some of the cruelest oppressions of this century. A recurring theme in his autobiography is an apology for having accomplished so little. His standards must have been very high, probably unreachable. He frequently attributed his survival to luck, giving himself far less credit than he deserves. Many of his best works were produced long after the age at which others retire. He stood before a large audience in 1974, defending his position on friction at the age of 76. He was prepared to present a paper to the St. Louis section of the American Society for Metals in October 1978 at the age of 80, but death intervened. It would have been good to hear him and to engage in debate and discussion with this great man once again but that is never more to be.

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Editor's note

A review "Adhesion in friction" by J. J. Bikerman appeared in *Wear*, 39 (1976) 1 - 13.