Rapport BIPM-82/9

THE NEWTONIAN GRAVITATIONAL CONSTANT :

An Index of Measurements

George T. Gillies

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Bureau International des Poids et Mesures
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ABSTRACT

The Newtonian Gravitational Constant, "G", has probably been measured more often but, interestingly, with less precision than any other physical constant of fundamental importance. In an effort that has spanned more than a century to connect gravitation to the other forces of nature, over 200 experiments on G have been completed and reported; but many of them have not been reported in what would now be considered to be the open literature. This paper is an attempt to carry MacKenzie's and Poynting's bibliographies forward from the 1800's to the present; and thereby include as many as possible of the experimental results on G that have been obtained since 1900.

I. Introduction

If one were to catalogue the tools of precision measurement, an unusually high number of the listings would claim as their genesis the precision measurement of the Newtonian Gravitational Constant, herein simply referred to as "G". These tools would include the torsion balance, the optical lever, the quartz fiber, synchronous detection techniques, ultra-high precision rotations and many others. Yet G stands alone as the only fundamental constant currently known to little better than one part in a thousand although there are three measurements claiming accuracies of one part in ten thousand. In parallel with these efforts to measure the absolute value of G, there has also been a wide variety of experiments aimed at linking the gravitational force to the other forces of nature. All such efforts to date have had the singularly unique result of demonstrating that gravity, indeed, stands alone - the last of the great classical mechanisms - in spite of its modernized presentation via general relativity.

Classical gravitational physics has been like this, and foreseeably will continue to be like this. The reason why is that, to this date, no one has succeeded in isolating sufficiently well the gravitational interaction between laboratory masses to the point where other disturbing forces or experimental uncertainties do not dominate the measurement, at least at levels above those at which other phenomena might be expected to occur.

It is nevertheless both interesting and important to catalogue the large body of work done already in the hope that a thorough listing of the experimental facts concerning our knowledge of G will stimulate future work on this constant and the force that it governs.

Part of the motivation for this paper lies in the fact that much of the work on G was reported obscurely in spite of the fact that most experiments have been carefully designed and completed. It was, therefore, a challenge to extract from various libraries, archives and private collections the existing data that, when collectively viewed, will help to focus attention on just exactly what has been done and, more importantly, what has <u>not</u> been done in this field.

This work is meant to be a bibliography and, at present, only that. Owing to the unusually large number of references cited, any thorough discussion of all the results would have taken up more space than was available here. Nevertheless, there is a small amount of annotation provided in the following pages for each of the thirteen sections of the bibliography. These areas into which the papers have been classified are listed below:

1. Measurements of the absolute value of G and reports of important subsidiary technology.
2. Important comments and reviews of measurements of G.
3. Measurements of gravitational permeability or absorption.
4. Measurements of the local directive action of the gravitational force.
5. Measurements of the dependence of G on the physical state of masses.
6. Measurements of the dependence of G on the chemical state of masses.
7. Measurements of the dependence of G on temperature.
8. Measurements of the dependence of G on the radioactivity of masses.
9. Measurements of the dependence of G on the electromagnetic energy content of masses.
10. Measurements of the dependence of G on inter-mass spacing.
11. Measurements of the dependence of G on time.
12. Measurements of spontaneous matter creation (related to 11).
13. Measurements of the dependence of G on the state of quantization of the test masses and their orientation with respect to the "fixed stars".

There are about 850 references cited in these 13 sections. There is some duplication, as a few of the papers contain two or more experimental results each in a different area. Duplicate listings constitute about 5% (or less) of the total, however. The references are listed alphabetically in each section with a chronological sublisting for each author in each section. The order of the items in each of the references follows the ISO recommendations as closely as possible. Abbreviations for the journal titles follow the American Institute of Physics <u>Style Manual</u> wherever possible. For those journals not listed there, the abbreviations in the ISI Current Contents indexes have been used. Those listings that have the author's name(s) marked with an asterisk have not been consulted at the time of this writing. References to entries in the various abstracting journals have not been given except for a few special cases where the abstracted article was judged to be published obscurely.

Not all of the listings in the Mackenzie (1900) and Poynting (1894) bibliographies were repeated here. Some, like those referring to the "Fr. Bertier" Controversy of the late 1700's/early 1800's, have little scientific merit and were omitted.

Sections 11 and 12 contain several references to instrumental papers in addition to those actually quoting significant results. In particular, the work at the University of Virginia is listed in detail.

II. Experimental Studies and Critical Analyses of G

1. Measurements of the Absolute Value of G and Reports of Important Subsidiary Technology

The history of the measurement of the universal gravitational constant begins with geophysical studies of a related physical quantity, the mean density of the earth. These efforts started with attempts to measure the attraction of individual mountains, measurements of strata of the earth's crust as a function of depth in various mines, and they are continuing with measurements of the attraction of layers of water in large level-controllable lakes and in the oceans.

Chronologically, the torsion balance methods came next, and these gave the most reliable results until the advent of the torsion pendulum technique. The balance-beam methods were studied during the late 1800's, and today all three of these methods are being developed in experiments aimed at accuracies of one in 10^5.

Numerous miscellaneous methods have also been developed. These include resonant torsion pendulums, vertical pendulums, near zone gravity wave detector excitation, and long period horizontal pendulums. There have also been several proposed satellite determinations of G, but so far no such measurements have actually been made (although spacecraft have been important in measuring the time rate of change of G and the geocentric constant, i.e., $G \times M_{earth}$).

The early works on G, particularly those of Cavendish, Reich and Baily, have been reviewed hundreds of times, and the principal papers of these workers are summarized and paraphrased in most undergraduate textbooks on physics. There are, however, about 60 other determinations of G that are in the open literature. Some of these are well known too, particularly those of Boys, Poynting, Braun, Heyl and the Beams-Deslattes-Luther-Towler collaboration between the University of Virginia and the U.S. National Bureau of Standards.

Of the latest works, there are three that claim accuracies near one part in ten thousand. They are summarized in Table I. The agreement between the values is only fair, however, even at the 10^{-3} level.

Table I

Author	Year	Experimental Technique	$(G \pm \Delta G) \times 10^{11} m^3 kg^{-1} s^{-2}$
Facy, Pontikis	1972	Resonant Pendulum	6.6714 ± 0.0006
Sagitov et al.	1977	Torsion Pendulum	6.6745 ± 0.0008
Luther, Towler	1982	Torsion Pendulum	6.6726 ± 0.0005

All uncertainties quoted in Table I as well as that in the CODATA value below represent one standard deviation.

Even if ultimately measured in a drag-free satellite, where external horizontal gravity gradients would not influence the balance, measurements of G would still be limited by the uncertainties arising from density gradients in the materials used. This would probably occur somewhere between the 10^{-5} and 10^{-6} level. At that point, a totally different approach to the measurement of G will become necessary.

Our currently accepted value, the CODATA value, is from 1973:

$$G = (6.6720 \pm 0.0041) \times 10^{-11}\ m^3 kg^{-1} s^{-2}.$$

2. Important Comments and Reviews of Measurements of G

There are four thorough reviews of the measurements of G: two dating to the late 1800's and two more recent ones. Poynting and, later, MacKenzie summarized the contemporary knowledge of G and, for that matter, all of gravitational physics, in books printed in 1894 and 1900, respectively. Sagitov (1969) recently published a similar work on G, although he omitted many references to experiments probably judged by him to be of secondary importance. Most recently, de Boer (1982) has contributed a review article which catalogues the recent major experiments and presents the results and uncertainties together on easily readable graphs. There are several other reviews of the experiments, and these are listed in the bibliography. It should be mentioned that each successive edition of the Encyclopedia Britannica articles on "Gravitation" contain interesting and relatively thorough sections on G that are very useful.

In addition to the review articles on G, there are a large number of papers, both old and new, that comment on or discuss certain measurements of G, propose new measurement techniques, or analyze probable experimental limitations. Some of these are worth consulting, since errors have occasionally appeared in the main papers of the principal investigators. The titles of the papers in this section of the bibliography usually indicate the relevance to a certain experiment or class of experiments.

3. Measurements of Gravitational Permeability or Absorption

Although not widely known, one of the most thoroughly researched aspects of gravitational physics is the question of the existence of a gravitational analogue to magnetic permeability. The pursuit of this question, i.e., the dependence of G on the density of the matter intervening between the interacting masses, began with a null result in the late 1800's. It continued until recent times, always with null results, but with ever-increasing accuracy. We now know that if gravitational energy is, in fact, absorbed by any intervening material, it occurs at a level such that, when measured in terms of G, the result is $(\Delta G/G)_{abs} < 10^{-16}$.

At first these measurements were made by employing a Cavendish balance with a cylindrical screen separating the suspended dumb-bell from the attracting masses. Each screen was made of a different type of material, and all the materials had different densities. The screens were sequentially changed and the measurements of G subsequently made were analyzed for a resulting effect. Later, Majorana began a long series of experiments using a balance-beam and claimed to have found a result at the 10^{-11} level, but subsequent work by himself and others disproved this. The most sensitive measurements have been made in recent times by several workers studying the period shift in horizontal pendulums during a total solar eclipse. In every case, however, the results have been null except for the results of Allais and, later, Saxl and Allen which are seldom discussed.

Unless a new theory predicts a permeability effect substantially different from that empirically sought so far, it is difficult to see where the motivation would arise for new experiments in this area. This is especially so since recent gravitational analogues of electromagnetism predict that the "gravitational permeability of free space" is only $\frac{16\pi G}{c^2} \approx 10^{-26}$ m/kg (Forward, 1961), a very small effect indeed!

4. Measurements of the Local Directive Action of the Gravitational Force

Since so many properties of crystalline materials depend upon the direction of observation (e.g. refractive index, local density distribution, thermal conductivity, etc.), it seemed reasonable to question the constancy of G within crystalline materials as well. This was first done by MacKenzie, then later by Poynting although no anisotropy in the value of G was found in either case at $\approx 10^{-3}$ and 10^{-4} levels, respectively. Heyl did an exhaustive experiment in this area in 1924 and, by weighing crystals from each of the five non-isometric groups, was able to put a limit of $(\Delta G/G)_{ca} \approx 10^{-9}$, thereby effectively eliminating any doubt about it.

It has been suggested that one should not expect to find such anisotropies in general because they would lead to a violation of conservation of momentum. Nevertheless, the weakness of the gravitational force and the singular properties of some crystals made this, temporarily at least, an attractive area of research.

5. Measurements of the Dependence of G on the Physical State of Masses

This category is a rather general one, although it is possible to classify various types of experiments within it. Specifically, there have been measurements of G involving test masses and attracting masses of various geometrical shapes. For example, spheres, cylinders, rods, rings, and irregular masses have been used. In fact, a cylindrical configuration having the sphere-like field of a point source is presently under study. Attracting and test masses in the gaseous, liquid and solid state have been (or are being) studied, as well as masses which undergo a change of state during the experiment. In all cases, no departure from true constancy of G has been observed, at least within the levels of the experiments' precision. When one considers that the sun, a plasma, and its planets (gas, solid and liquid combinations) have orbits which conform precisely to the inverse square law (with only minor relativistic corrections), it is seen that this law is indeed well obeyed. The references cited here are representative examples of various types of experiments involving gases, liquids and solid masses of various shapes. Some of these citations are listed in other more appropriate sections of the bibliography too.

6. Measurements of the Dependence of G on the Chemical State of Masses

This area of research is usually interpreted as being a test of the weak equivalence principle of General Relativity, i.e. a determination of the equivalence of gravitational and inertial mass. The various searches for a non-zero Eötvös ratio which test this equivalence are catalogued by Will (1981) and are not included here, except for a few special cases given below.

The earliest measurements in this area involved pendulums of the same mass but made of different materials. Eötvös and his contemporaries expanded this to include torsion balances and balance-beams which had masses of different materials attached to them and which oscillated in the time-varying field of the sun as measured at the surface of the earth.

Several workers studied the interesting question "Does G vary while the test mass undergoes a chemical reaction?" but, in all cases, equilibrated or reacting, null results have been obtained. This area has not been without controversy, however. C.F. Brush claimed to see a difference in pendulum periods between pendulums made of bismuth and those of zinc. His observations were ultimately explained by a lack of inclusion of the buoyancy of air in his calculations.

Although not strictly belonging to this category, the experiment of L. Kreuzer (1966), at Princeton, is included here because it has been interpreted by some as providing evidence for a variation of G over the elements of the periodic table. This claim was subsequently refuted, but caused some interest at the time.

7. Measurements of the Dependence of G on Temperature

Early in this century, there were two attempts to measure with balance-beams a dependence of G on the temperature of the attracting masses. They both produced null results but were nonetheless open to discussion. This was so for two reasons. First, there were well-known difficulties in experiments wherein two masses at different temperatures were used in a high-precision balance; and second, the unknown thermal profile of the earth immediately below the balance would seem to make an exact repetition of the experiment impossible, because any thermal dependence of gravity would presumably affect the earth's field too (and how can one control the temperature of the earth?).

Professor Shaw and his students, therefore, constructed a Boys-type balance in which the attracting masses could be heated. They measured G and analyzed their data in the form $G = G_0(1 + \alpha T)$. At first they found $\alpha \approx 10^{-5}\ {}^\circ C^{-1}$. This result created great interest and several papers were written discussing it. A careful repetition of their original work showed, though, that after removing troublesome convection effects, $\alpha < 2 \times 10^{-6}\ {}^\circ C^{-1}$, which effectively settled the issue in the negative. There do not seem to have been any other experiments following this one. Perhaps this is because it was realized that the large temperature difference between the earth and sun, when compared with the much smaller difference between the earth and moon, should have highlighted the existence of the effect. Instead, both orbits serve only to verify that the inverse square law is, in fact, independent of temperature. In questions of this type, however, scale factors may be important; and even though Poynting's and Southerns' balance-beam experiments (laboratory scale) in the earth's field produced null results at the 10^{-9} level, Shaw's experiment with isolated gravitational forces (also at laboratory scale) was 2 000 times less sensitive than either of theirs. So there may still, perhaps, be effects to be discovered.

8. Measurements of the Dependence of G on the Radioactivity of Masses

One very interesting area of research in this century has been the search for a connection between gravitation and what we now know to be the nuclear forces. Studies in this area have involved a wide variety of experimental techniques. Several famous physicists have worked in this area, including G. Sagnac, P. Zeeman, A. Compton and J.J. Thomson, each lending their own special expertise to this difficult problem.

Compton, for instance, produced a large and controllable pseudo-gravitational (centrifugal) field by rotating samples of radium at high speeds. He concluded that this did not affect the radioactivity by more than 10^{-3}. Thompson's uranium-pendulum experiment (carried out in more detail by Southerns) showed no gravitational coupling to the sample's radioactivity at the level of 5×10^{-5}. All other measurements also produced null results, except for that of R. Geigel who claimed to have seen a small weight change in a nonradioactive sample hanging on a sensitive balance when a radium salt sample was placed nearby. He interpreted this as an absorption of radioactivity which led to an increase in the gravitational potential energy of the nonradioactive sample. W. Kaufmann shortly after, however, uncovered a thermal effect which explained the apparent weight change. No one since then has repeated Geigel's experiment.

9. Measurements of the Dependence of G on the Electromagnetic Energy Content of Masses

At the same time as the searches for a radioactivity-gravitational force coupling were under way, there was a parallel effort in progress aimed at finding an electromagnetic-gravitational coupling.

These searches typically involved weighing samples of steel in magnetized and unmagnetized states or charged and uncharged states.

The very much larger size of the electromagnetic forces always makes experiments of this kind very difficult, and careful attention must be paid to the shielding of undesirable electromagnetic couplings to the laboratory which would otherwise make the results ambiguous. In spite of this, null results were always reported.

At present, J.F. Woodward is repeating (with much higher precision) the early work of Faraday and Blackett in search of an electrogravitational effect, but it is not clear at this point what a positive result in these experiments would mean in terms of the value of G or the gravitational inverse square law. His preliminary results are included in this bibliography anyway, for the sake of completeness. The reference section of his paper refers the reader to citations of earlier work along that specific line.

10. Measurements of the Dependence of G on Inter-mass Spacing

The past decade has seen a great deal of research in this area, and most of the effort was motivated by the work of D. Long at Eastern Washington University. He claimed that an analysis of past measurements of the absolute value of G showed a distance dependence, which he later tested experimentally. His positive result produced great interest and motivated about ten groups to undertake experiments of their own, most of which now claim null results. The fundamental importance of this question has caused it to remain open, however, and both theoretical and experimental work will probably continue for some time to come.

Here too, experiments have been done on many scales of distance, ranging from 2 cm up to several kilometers. There have been analyses of the free oscillations of the earth in terms of how they might be influenced by a non-zero G(R); and on the still larger scale, the motion of the planets has been seen to confirm the inverse square law to an amazingly high precision (except for the previously mentioned relativistic corrections).

The majority of the latest experiments have been designed to be high sensitivity null measurements, although the early work (and that of Long) instead involved measurements of the absolute value of G at two or more different mass spacings. While a workable scheme in principle, the absolute measurements are usually burdened with large drifts and metrological difficulties. This sometimes makes their results open to question.

11. Measurements of the Dependence of G on Time

Perhaps no other area of gravitation is of greater interest to theorists and cosmologists than the possibility of variations of G in time. There have been many theories calling for a time-varying G, each having its own implications on the behavior of matter and radiation at the early moments of the universe.

Here again, the experiments fall into the three familiar categories of laboratory, geophysical and astronomical. If such an effect exists, it is agreed that it must be very, very small; probably on the order of $\dot{G}/G \approx 10^{-11}$ year^{-1}. Few laboratory tests of any kind have been done at this level, and it is not surprising that the existing laboratory tests of this effect are limited at the level of $\dot{G}/G \approx 10^{-7}$ year^{-1}. Several experiments with test masses have been proposed for both earth-surface and orbiting laboratories which should be sensitive to the predicted 10^{-11} year^{-1} changes, but none has yet been completed.

The geophysical tests have usually involved studies of the expansion of the earth or investigations of a paleobiologic type. While these provide corroborating evidence, they are not usually accepted as hard proof because of the many uncertain factors involved. Wesson's contributions are the most complete in this area, and his book "Cosmology and Geophysics" (1978) should be consulted for a thorough review of geophysical investigations of $\dot{G}/G$.

The three astronomical tests of $\dot{G}/G$ are now yielding similar results and seem to show that $\dot{G}/G \cong -(6 \pm 2) \times 10^{-11}$ year^{-1}. These tests include: (1) lunar laser ranging from MacDonald Observatory in

Texas, (2) radar ranging of the inner planets, and (3) lunar occultation studies and determinations of the moon's orbit.

There are some miscellaneous tests of $\dot{G}/G$ as well, although before the existence of this effect is accepted as truly proven, it is likely that evidence from all three areas (laboratory, geophysical and astronomical) will have to be available and show good agreement.

12. Measurements of Spontaneous Matter Creation

Most of the theories that call for a non-zero $\dot{G}/G$ also require the spontaneous creation of matter. This is usually the result of a gauge condition; or is in response to satisfying some phenomenological requirement, such as maintaining constant density in the universe. In a Machian universe, the value of the gravitational constant and processes like matter creation are presumably coupled in such a way that the value (or existence) of one affects the other. Therefore, it seemed appropriate to include the known experimental tests, tests in progress, and proposed tests of this effect in this bibliography too.

In terms of categories, the $\dot{M}/M$ experiments are classifiable in the same way as the $\dot{G}/G$ experiments. There are substantially fewer of them, and only one laboratory experiment, that of S. Cohen and J. King, has yielded a result, which was null at the $\dot{M}/M = 10^{-23}\ s^{-1}$ level. The spinning-rotor measurement currently in progress at the University of Virginia seems to be the most promising experiment for the immediate future, although others are also in progress.

13. Measurements of the Dependence of G on the State of Quantization of the Test Masses and their Orientation with Respect to the "Fixed Stars"

There have been two proposals for measuring G in terms of h, the Planck constant. These experiments, if ever done, will be the first direct tests of a quantum structure of the gravitational field. One indirect test by D. Page and C. Geilker has been carried out but is disputed.

An apparatus has been constructed at the Cavendish Laboratory of Cambridge University in England for the purpose of searching for a variation in G with respect to the fixed stars. Although this is presently inactive, it is hoped that such an experiment can be done eventually, as it represents a kind of "universal gravimetry" which, if sensitive enough, should yield results of fundamental significance.

Summary of Section II

The results of the different searches for variations in G are summarized in Table II. For each category, the experiment claiming highest precision is quoted, unless otherwise stated.

Some results entered in Table II are dimensionless. In these cases, the authors listed had tried to set limits on some appropriate dimensionless scale factor. Their original results (where necessary) have been translated into the more familiar $\Delta G/G$ format for presentation here.

Table II

Effect	Author	Year	Result ($\Delta G/G$)
Gravitational permeability or absorption	M. Caputo	1962	$< 6 \times 10^{-16}$
Directive action of gravitational force	P.R. Heyl	1924	$< 10^{-9}$
Dependence of G on physical and/or chemical states of matter	For a review, see C. Will	1981	$< 10^{-12}$
Temperature dependence via a Cavendish balance	P.E. Shaw and N. Davy	1922	$< 10^{-6}\ {}^\circ C^{-1}$
Temperature dependence via a common balance	J.H. Poynting and P. Phillips	1905	$< 10^{-10}\ {}^\circ C^{-1}$
Gravitation/ radioactivity coupling	P. Zeeman	1918	$< 5 \times 10^{-8}$
Dependence of G on magnetization of matter	M.G. Lloyd	1909	$< 5 \times 10^{-12}$ (Gauss)$^{-1}$
Dependence of G on electrification of matter	L. Simons	1922	$< 1.2 \times 10^{-7}\ V^{-1}$
G(R)	R.E. Spero, et al.	1980	$(1 \pm 7) \times 10^{-5}$
$\dot{G}/G$ (Astronomical)	For a review, see T. Van Flandern	1981	$(-6 \pm 2) \times 10^{-11}$ year^{-1}
$\dot{G}/G$ (Laboratory)	D.R.F. Curott	1965	$< +6.2 \times 10^{-7}$ year^{-1}
$\dot{M}/M$ (Laboratory)	S. Cohen and J.G. King	1969	$< 4 \times 10^{-23}\ s^{-1}$

III. Closing

As mentioned previously, this work is meant to be a resource bibliography, not a critical review of the status of each of the various areas treated here. It is hoped that the readers of this bibliography will benefit from the relatively comprehensive listing of references given here. Further, it is hoped that readers will respond with missing references if possible. This will be the only way that the "holes" can be filled, since the work to bring the bibliography to the present level has been more than one person should attempt alone.

As much useful information as possible has been put into each citation. References to work done in the Soviet Union are harder to get (in hard copy) than most others. This is because there does not seem to be any direct exchange mechanism between Soviet libraries and Western libraries. Nevertheless, probably most of the important works published there have been obtained by the author and appropriately catalogued.

The references have been recorded at the BIPM using computerized word processors. This makes it possible to seek, sort and list them by author, date, journal and key word(s). The flexibility of this system makes this bibliography, in fact, a gravitational physics data base. Searches of it by non-BIPM personnel can be made under special arrangement.

English translations of some non-English articles in the bibliography (except those marked with an asterisk) are available from the author, also via special arrangement.

The addresses and telephone numbers of the research libraries that have been most helpful in this work are given below.

Library of the United States National Bureau of Standards
U.S. Department of Commerce
Washington, D.C. 20234
USA
(301) 921-2318

Superintendant of Documents
U.S. Government Printing Office
Washington, D.C. 20402
USA
(202) 783-3238

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
USA
(703) 487-4650

The Library of Congress
Photoduplication Service
10 First Street S.E.
Washington, D.C. 20540
USA
(202) 426-5000

Research Library
Microreproduction Laboratory, Room 14-0551
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, Massachusetts 02139
USA
(617) 253-5668

The Science and Technology Information Center
Clark Hall
University of Virginia
Charlottesville, Virginia 22901
USA
(804) 924-7209

Centre de Documentation Scientifique et Technique
26, rue Boyer
F-75971 Paris Cedex 20
France
(1) 358-35-59

British Library Lending Division
Boston Spa
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United Kingdom
(0937) 843434

The author shall continue to add to this bibliography as more work on G is done in the future and as other previous reports are uncovered and made available. It is possible that there may be, therefore, a future updating of the present bibliography if there is sufficient reason and demand.

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