The Material Intricacies of Coulomb’s 1785 Electric Torsion Balance Experiment

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Abstract: Contemporary scholars are engaged in a debate over whether Charles Augustin Coulomb’s results that he presented in his 1785 and 1787 memoirs to the Paris Academy of Sciences were attained experimentally or theoretically. In this paper, we study Coulomb’s famous 1785 electric torsion balance experiment through analysis of relevant texts and, more importantly, through a replication that is more faithful to Coulomb’s original design than previous attempts. We show that, despite recent claims, (1) it has so far proved impossible to obtain the same results reported by Coulomb in his paper of 1785, (2) Coulomb’s published results are most likely atypical, and (3) electric torsion balance experiments degenerate quickly when parameters are altered by small amounts.

Keywords: Charles Augustin Coulomb, Coulomb’s Law, Torsion Balance, Experiment, Electric Force, Eighteenth Century Electricity, Replication

Abbreviated Title: Material Intricacies of Coulomb’s Torsion Balance

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INTRODUCTION: THE CONTROVERSY OVER THE EXPERIMENTAL JUSTIFICATION OF THE FUNDAMENTAL LAW OF ELECTROSTATICS

In 1785 Charles Augustin Coulomb (1736-1806) presented to the Paris *Académie Royale des Sciences* his first memoir on electricity and magnetism[1] which, along with his 1787 second memoir,[2] would lead physicists to name the fundamental law of electrostatics as 'Coulomb's law.' The law describes the force between two electrically charged bodies as directly proportional to the product of the charges on the bodies and inversely proportional to the square of the distance between the bodies. In this sense, it is analogous to Newton's law of gravitation. Coulomb is best remembered for his work on electricity and magnetism, which is considered by many his most important research.[3] However, Coulomb made significant experimental contributions to other sciences. Kragelsky and Schedrov, authors of the *locus classicus* book on the history of friction, state that "Coulomb's contributions to the science of friction were exceptionally great.

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[1] C.A. Coulomb, "Premier Mémoire sur l'Électricité et le Magnétisme. Construction & usage d'une Balance électrique, fondée sur la propriété qu'ont les Fils de métal, d'avoir une force de réaction de Torsion proportionnelle à l'angle de Torsion," *Mémoires de l'Académie Royale des Sciences* (1788): 569–577.

[2] C.A. Coulomb, "Second Mémoire sur l'Électricité et le Magnétisme. Où l'on determine suivant quelles lois le fluide magnétique ainsi que le fluide électrique agissent soit par repulsion, soit par attraction," *Mémoires de l'Académie Royale des Sciences* (1788): 578–611. This memoir was dated 1785 in the Academy's manuscript minutes, but it was actually read on February of 1787; see C.S. Gillmor, *Coulomb and the Evolution of Physics and Engineering in Eighteenth-Century France* (Princeton: Princeton University Press, 1971).

[3] For an example of this opinion, see I. Falconer, "Charles Augustin Coulomb and the Fundamental Law of Electrostatics," *Metrologia* 41 (2004): S107–S114.

Without exaggeration, one can say that he *created* this science."[4] Coulomb's 1773 memoir on statics,[5] for which he won an Académie prize competition, is described as "perhaps the finest *engineering* memoir delivered at the Academy during Coulomb's lifetime"[6] — a memoir that "… laid the foundations of the modern science of soil mechanics…"[7]

Yet, in recent times, Coulomb's status as an experimenter has been challenged. The results announced in Coulomb's 1785 memoir, as well as the experimental data Coulomb attained with his torsion balance in the following years, have come into question.

In 1992, Peter Heering, noticing that Coulomb's law was strongly contested in parts of Europe (especially in Germany) after its publication, queried whether Coulomb attained the results described in his 1785 memoir experimentally or from theoretical considerations.[8] By paying close attention to Coulomb's 1785 memoir and replicating the electric torsion balance, Heering provided both experimental and textual evidence

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[4] I.V. Kragelsky and V.S. Schedrov, *Razvitia Nauki o Trenii–Sookoi trenia* (*Development of the Science of Friction–Dry Friction*), Moscow (1956): 52, quoted in Gillmor, *Evolution of Physics and Engineering* (ref. 2), 136.

[5] C.A. Coulomb, "Essai sur une application des règles de Maximis & Minimis à quelques Problèmes de statique, relatifs à l'Architecture," *Mémoires de Mathématique & de Physique, présentés à l'Académie Royale des Sciences par divers Savans, & lûs dans ses Assemblées* 7 (1776): 343-382. Republished in J. Heyman, *Coulomb's Memoir on Statics: An Essay in the History of Civil Engineering* (Cambridge: Cambridge University Press, 1972).

[6] Gillmor, *Evolution of Physics and Engineering* (ref. 2), 81.

[7] Heyman, *Coulomb's Memoir on Statics* (ref. 5), vii.

[8] Peter Heering, "On Coulomb's Inverse Square Law," *American Journal of Physics* 60 (1992): 988–994.

against the thesis that Coulomb's attained his 1785 results experimentally.[9] Heering's experimental evidence included his inability to successfully replicate Coulomb's experiment as it is described in the 1785 memoir, his identification of unavoidable sources of error, and more recently,[10] his failure to attain portions of the result described in Coulomb's 1784 wire-torsion experiments.[11] Accordingly, Heering claimed that

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[9] See the following works by Peter Heering: Heering, "Coulomb's Inverse Square Law" (ref. 8); Peter Heering, "Récherches Théoretiques et Expérimentales sur la Loi Fondamentale de l'Électricité: C. A. Coulomb's Experimental Proof of the Inverse Square Law," August 1992, presented at International Workshop on Replications of Historical Experiments in Physics (Carl von Ossietzky Universität Oldenburg); Peter Heering, "The Replication of the Torsion Balance Experiment: The Inverse Square Law and its Refutation by early 19th-Century German Physicists," in *Restaging Coulomb*, ed. C. Blondel and M. Dörries, *Restaging Coulomb: Usages Controverses et Réplications autour de la Balance de Torsion* (Firenze: Leo S. Olschki, 1994): 47–66; Peter Heering, "Das Grundgesetz der Elektrostatik. Experimentelle Replikation, wissenschaftshistorische Analyse und didaktische Konsequenzen" (PhD dissertation, Carl von Ossietzky Universität Oldenburg, 1995); and Peter Heering, "Regular Twists: Replicating Coulomb's Wire-Torsion Experiments," *Physics in Perspective* 8 (2006): 52-63. Also see Peter Heering and Gérard Chevalier, "Balances d'hier et d'aujourd'hui," *Les Cahiers de Science & Vie* 26 (1995): 66-72. Heering's 2006 piece concentrates on Coulomb's 1784 memoir on torsion. In our discussion of Heering's work we ignore the textual evidence he provided for his thesis (that Coulomb attained his 1785 results theoretically) because this source of evidence is analyzed and discredited in A.A. Martinez, "Replication of Coulomb's Torsion Balance Experiment," *Archive for History of exact Sciences* 60 (2006): 517-565. See pp. 538-540 of Martinez's work for details.

[10] See Heering "Regular Twists" (ref. 9).

[11] C.A. Coulomb, "Recherches Théoriques et Expérimentales sur la force de torsion, & sur l'élasticité de fils de métal: Application de cette théorie à l'emploi des métaux dans les Arts & dans différentes balances de torsion, pour mesurer les plus petits degrés de force. Observations sur les loix de l'élasticité & de coherence," *Mémoires de l'Académie Royale des Sciences* (1787): 229–269.

"Coulomb did not find the inverse square law by doubtful measurements from his torsion balance experiments but by theoretical considerations."[12] John L. Heilbronn admits that it "… appears from Heering's resourceful labor that Coulomb either faked his numbers completely or obtained them under experimental conditions materially different from those he reported."[13]

Heering's work gave rise to a plethora of historically oriented theories and claims about the experimental methods of Coulomb and his contemporaries, as well as the practices of scientific reporting of Coulomb's time.[14] For example, Isobel Falconer has

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[12] Heering, "Coulomb's Inverse Square Law" (ref. 8), 993.

[13] J.L. Heilbron, "On Coulomb's Electrostatic Balance," in Blondel and Dörries, "*Restaging Coulomb*" (ref. 9, 151-161), 151.

[14] See, among others, C. Blondel, "La 'Mécanisation' de l'électricité: idéal de mesures exactes et savoir-faire qualitatifs," in Blondel and Dörries, "*Restaging Coulomb*" (ref. 9, 99-119); Falconer, "Fundamental Law of Electrostatics" (ref. 3); L. Fregonese, "Two Different Scientific Programmes: Volta's Electrology and Coulomb's Electrostatics," in Blondel and Dörries, "*Restaging Coulomb*" (ref. 9, 85-98); Heering, "Coulomb's Inverse Square Law" (ref. 8); Heering, "Coulomb's Experimental Proof" (ref. 9); Heering, "Replication of Torsion Balance Experiment" (ref. 9); Heering, "Das Grundgesetz der Elektrostatik" (ref. 9); Heering, "Regular Twists" (ref. 9); Heering and Chevalier, "Balances" (ref. 9); Heilbronn "On Coulomb's Electrostatic Balance" (ref. 13); C. Licoppe, "Coulomb et la 'Physique Experimentale': Pratique Instrumentale et Organisation Narrative de la Preuve," in Blondel and Dörries, "*Restaging Coulomb*" (ref. 9, 67-83); and Pestre, "La Pratique de Reconstitution des Expériences Historiques, Une Toute Première Réflexion," in Blondel and Dörries, "*Restaging Coulomb*" (ref. 9, 17-30). Martinez, "Coulomb's Torsion Balance Experiment" (ref. 9), 534 also notes some suggestions made (with regard to Coulomb's experimental methods) by Jed Buchwald and Maria Trumpler. Those suggestions can be found in S. Dickman, "Could Coulomb's Experiment Result in Coulomb's Law?," *Science* 262 (1993): 500-501. See Dickman's work for a colloquial overview of the controversy prior to Martinez's 2006 recreation.

suggested that it is possible that Coulomb's 1785 memoir was an attempt to establish priority over the torsion balance as well as an attempt to promote it as a valid experimental instrument, rather than to demonstrate the fundamental law of electrostatics.[15] Further, when discussing his research concerning Coulomb's 1784 memoir on torsion, as well as the 1785 and 1787 memoirs on electricity and magnetism, Heering goes so far as to suggest that the memoirs represent a "rejection of politically dangerous theories" through an "affirmation of the fruitfulness of the new style of scientific experimentation" (as portrayed in Coulomb's 1784, 1785 and 1787 memoirs).[16]

However, more recently, Alberto A. Martinez succeeded in replicating Coulomb's 1785 results, thus bringing forth strong evidence that Coulomb's results had been attained experimentally. Consequently, and in direct disagreement with prior scholars such as Heering, Martinez claims that "Coulomb obtained his numbers from experiment. His results were not unusual, they were almost certainly typical."[17]

In this paper, we engage this controversy over Coulomb's 1785 memoir. Our goal is to contribute to its resolution primarily through an historically accurate replication of the electric torsion balance, as it is described Coulomb's original memoir. We replicated Coulomb's torsion balance experiment and our results tend to confirm those of Martinez while diverging from his in important respects. Briefly, we found that it is possible to replicate the torsion balance experiment, as Coulomb describes it, in an *approximately* successful manner. However, achieving results very close to those

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[15] Falconer, "Fundamental Law of Electrostatics" (ref. 3), 111-112.

[16] Heering, "Regular Twists" (ref. 9), 61-62.

[17] Martinez, "Coulomb's Torsion Balance Experiment" (ref. 9), 547.

published originally in Coulomb's memoirs (and more recently by Martinez), is *not* possible due to a source of error that is most likely unavoidable. This source of error has not been identified in previous historical accounts of the experiment.[18] A host of questions follow:

- Was Coulomb aware of such a source of error?
- If so, did he account for it? If so, by what means?
- More specifically, what exactly is the data set that Coulomb describes in his 1785 memoir supposed to represent?

This paper will, we hope, mark some progress toward answering these questions. We maintain that Coulomb was most likely not aware of the source of error; thus, he did not account for it, and his data set, which clearly demonstrates the inverse square law, is atypical.[19,20]

The next section presents Coulomb's 1785 memoir along with his description of the apparatus and the experiment. Then, we discuss prior replications, concentrating on Martinez's replication, in order to motivate our current project. We first discuss the manners by which recent replications diverged from Coulomb's 1785 description and

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[18] We gather that Martinez (ibid.) noticed these sources of error but potentially misinterpreted them. We will elaborate on this issue in later sections.

[19] Whenever we translate Coulomb without identifying the translator, the translation is our own with extensive help from Katie Moriarty.

[20] The work presented here is very much a continuation of the work done by Heering and, even more so, by Martinez. In order to avoid repetition, we will direct the reader to prior work done on the torsion balance whenever it is appropriate. We will concentrate on our original contribution, as well as material that has already been covered by prior scholars but is essential for understanding and motivating our project.

then we proceed to question the historical validity of Martinez's replication. The following section presents our replication of the torsion balance along with results, emphasizing those aspects that diverge from prior replications. One subsection discusses our identification of an important error source in the torsion balance experiment, while the other elaborates on our claims that the success of the torsion balance experiment is highly dependent upon its material composition and that it degenerates quickly when parameters are altered. In the penultimate section, we make some preliminary steps toward answering questions regarding Coulomb's awareness of error sources, as well as the experimental methods he used for dealing with error sources. The final section summarizes our conclusions.

COULOMB'S 1785 MEMOIR AND THE ELECTRIC TORSION BALANCE

The fundamental law of electrostatics (Coulomb's law) describes the force between two (electrically charged) point-bodies as inversely proportional to the square of the distances between the point-bodies:

$$F_e = C/d^2 \tag{1}$$

F_e is the electric force, d is the distance between the point-bodies, and C is a constant that depends upon the amount of charge on the bodies and other constants of nature. In order to demonstrate that the electric force behaves as an inverse square law, Coulomb begins his 1785 memoir by recalling a result from his 1784 memoir on wire-torsion experiments.

There, Coulomb found that the "laws governing the torsion in a metal thread" are of the following kind:[21]

$$F_\tau = \mu B D^4/l \tag{2}$$

F_τ is the force due to torsion, μ is a constant characteristic of a particular metal, B is the angle of torsion (the total angle the wire is twisted through), D is the diameter of the wire, and l is the length of the wire. By coupling electrically charged bodies to a torsion balance, as will be described in detail below, and considering an equilibrium point where the torsion and electric forces are equal, one can attain the following relation:

$$F_e = C/d^2 = \mu B D^4/l = F_\tau \tag{3}$$

And, since C, μ, D, and l can be chosen as constants (that is, they do not vary in time between consecutive measurements), the torsion angle B will be proportional to the inverse square of the distance:

$$1/d^2 \propto B \tag{4}$$

In this manner, if the distance d between two bodies is halved to d/2 we expect the angle of torsion, and the corresponding force of torsion, to quadruple: $1/(d/2)^2 = 1/(d^2/4) = 4/d^2 \propto 4B \propto 4F_\tau$. It is this technique that Coulomb uses in his 1785 memoir to demonstrate the inverse square law of electrostatics.

After introducing the torsion-wire relation in equation (2), Coulomb proceeds to describe the construction of his electric torsion balance. This is followed by a presentation of his experiment and an explanation of the results. The memoir ends with four remarks about the experiment. We will follow a similar order of presentation, but

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[21] Coulomb, "Recherches Théoriques et Expérimentales" (ref. 11), 247. The choices of μ, B, D and l as the letters to signify the variables in the wire-torsion equation are Coulomb's.

for the description of the torsion balance we quote Coulomb at length. The reader is urged to follow the description by focusing on Figure 1, which is an illustration of Coulomb's electric torsion balance and its parts as it appears in the published memoir.[22]

> Over a glass cylinder [ABCD] 12 inches in diameter and 12 inches high, a flat plate of glass 13 inches in diameter was placed, which covers the entire structure. This plate has two holes of about 20 lines [≈4.5cm] in diameter, one of them at its center, f, on which a glass tube 24 inches high is placed… On top of the tube at h is placed a torsion micrometer, shows in detail in Fig 2. The top part of this micrometer, No. 1, has a knob b, index io, and a suspension clamp q, which fits into the hole G of part No. 2. Part No.2 is made up of a circle ab, which has 360° scale on its edge, and a copper tube Φ that fits into the hole H of part No. 3, which is attached to the top of the glass tube fh of Fig. 1.
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> The clamp q (Fig. 2, No. 1) has nearly the form of the tip of a crayon holder, which can be narrowed by means of the ring q. It is in this clamp that one end of a very fine sliver wire is placed. The other end of this wire is attached at P (Fig. 3) by means of a clamp on the rod Po. This rod is made of copper or iron and its diameter is barely one line [≈2.3mm.] The upper end P is split, making a clamp that is closed by means of the sliding ring φ. This cylinder is enlarged and pierced at C by a sliding needle ag. The whole weight of the cylinder must be such that it can keep the silver wire stretched without breaking it. The needle ag, as can be seen in Fig. 1, is suspended horizontally at its center and at about half the height of the glass container. *It is made either of a silk thread coated in Spanish wax or of a straw similarly coated, [and terminated from q to a in 18 lines (≈4cm) of length by]*[23] *cylindrical thread of shellac*[24]; at one end of this needle is placed a

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[22] Figure 1 of the present work includes within it five figures, which Coulomb labels "Fig. 1," "Fig. 2," and so on, in his description of the torsion balance.

[23] A slight translational variation appears in M.H. Shamos, *Great Experiments in Physics: Firsthand Accounts from Galileo to Einstein*, (New York: Dover Publications, 1959). On page 63 of that work, this phrase is translated as follows: "The needle… is made of either silk or thread coated with Spanish wax… It is about 18 lines long and terminates in a cylindrical thread of shellac…" Shamos's translation implies

> small ball which is made of pith[25] and is two to three lines in diameter [4.5-6.8mm]. At the end g is a small piece of paper soaked in turpentine; this paper counterbalances the ball a and slows down the oscillations.
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> We have said that the glass cover AC has a second hole m; it is through this hole that a small rod mφb is introduced. The lower part of this rod (φb) is made of shellac, and at b terminates in another small pith ball. Around the glass container , at the height of the needle, is a scale ZQ divided into 360 degrees. This scale was made for simplicity out of paper fastened around the container at about the height of the needle.…[26]

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that the needle is 18 lines long, but we, as well as Martinez (Martinez, "Coulomb's Torsion Balance Experiment" (ref. 9), 520), take the cylindrical thread of shellac, and not the needle, to be 18 lines long. Here is Coulomb's original text: "L'aiguille que l'onvoit (fig I) en ag, fufpendue horizontalement à la moitié à peu-prés de la hauteur du grand vafe qui la renferme, eft formée, ou d'un fil de foio enduit de cire d'Efpagne, ou d'une paille également enduite de cire d'Efpagne, & terminée depuis q jufqu'en a, fur 18 lignes de longueur, par un fil cylindrigque de gomme-laque…" (Coulomb, "Premier Mémoire sur l'Électricité" (ref. 1), 571).

[24] In footnote 9 of Martinez's work (Martinez, "Coulomb's Torsion Balance Experiment" (ref. 9), 520), Martinez identifies 'shellac' (or *gomme-laque*) as a sticky resin secreted from various lac insects. Shellac, along with turpentine and additional resins, is the main ingredient in Spanish Wax (*cire d'Espagne*).

[25] The 'pith' referred to here is a soft substance found on the inside eldenberry shrubs: "une petite balle de fureau" (Coulomb, "Premier Mémoire sur l'Électricité" (ref. 1), 571).

[26] Coulomb, "Premier Mémoire sur l'Électricité" (ref. 1), 570-571. The translation presented here is that of Shamos (Shamos, *Great Experiments in Physics* (ref. 23), 62-63). Emphasis added. See Martinez, "Coulomb's Torsion Balance Experiment" (ref. 9), 519-520 for another translation.

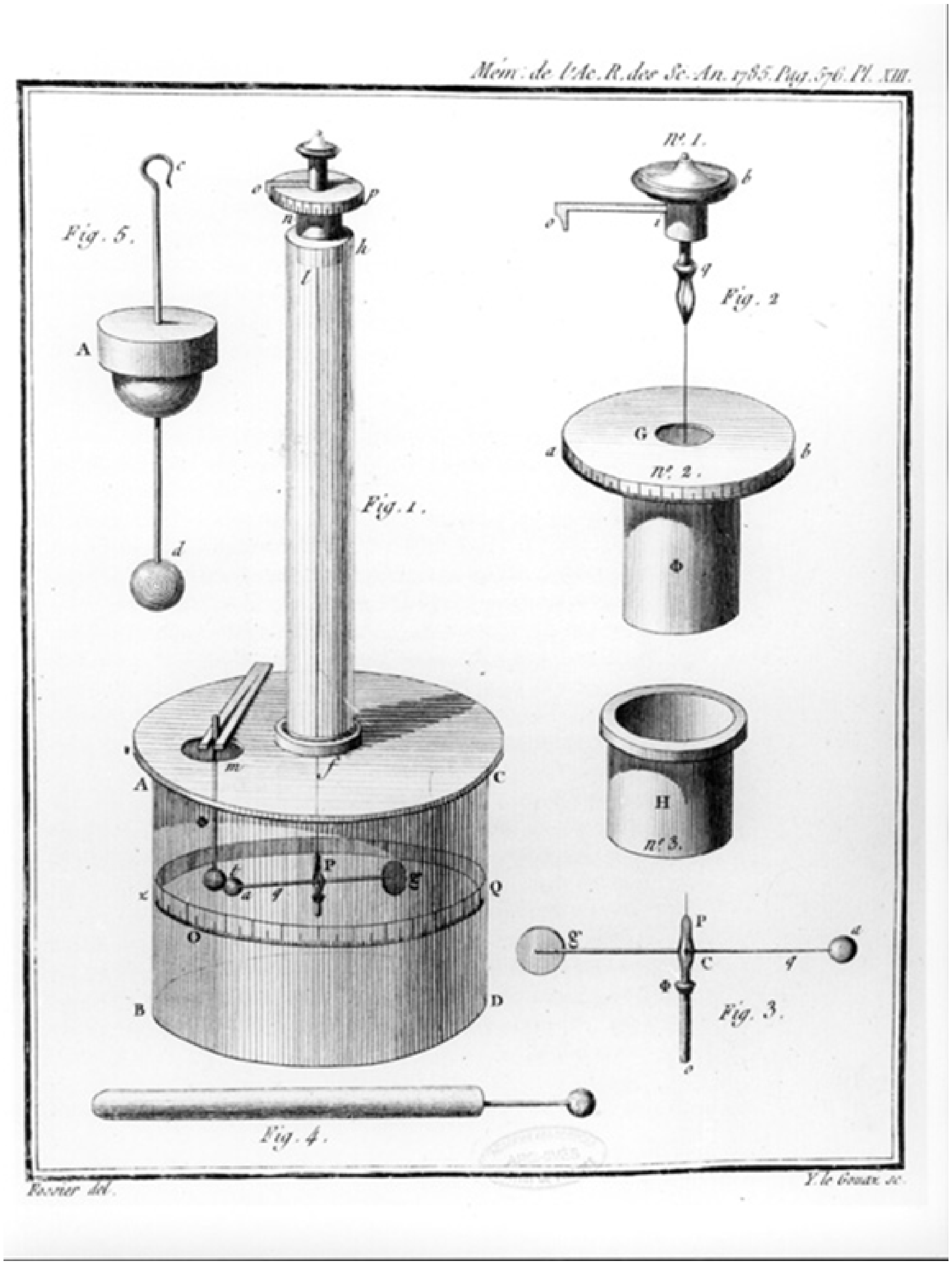

Figure 1. Coulomb's torsion balance of 1785. Reproduced from original (Coulomb, "Premier Mémoire sur l'Électricité" (ref. 1)).

After bringing the two pith balls together at the zero degree mark of the ZQ scale and grounding them, Coulomb continues to electrify them when they are in contact. The charge distributes approximately equally onto both pith balls and the balls repel each other. Following a few oscillations, the pith ball on the needle settles at a distance away from the stationary pith ball, a distance which Coulomb records. He then twists the micrometer by an amount which quadruples the total force of torsion and examines whether the distance between the pith balls converges to half, as would be the case if the electrostatic law was an inverse square law. In his memoir, Coulomb reports three trials "which are easily reproduced, and which will make evident the law of repulsion":[27]

> *First Trial*. Having charged the two balls with the head of a pin with the micrometer index set at *O*, the ball *a* of the needle is separated from the ball t by 36 degrees.
>
> *Second Trial*. Turning the suspension thread through 126 degrees by means of the knob *O* of the micrometer, the two balls are found separated and at rest at 18 degrees from one another.
>
> *Third Trial*. After turning the suspension thread through 567 degrees, the two balls are separated by 8 degrees and a half.[28]

We refer the reader to Martinez's work and Coulomb's original 1785 memoir for an in-depth analysis of the results. In short, these results show that as the force of torsion, which is proportional to the angle of torsion, is quadrupled from the first trial (36° of total torsion angle) to the second trial (144°=18°+126° of total torsion angle), the distance separating the balls approximately halves, and the same is true from the second to the third trial. Here we will use these results to calculate the exponent *n* of the distance d between the two balls in the electrostatic law (see eq. (1)) with the following equation:[29]

$$n = \frac{\ln \dfrac{\theta_a \cos(\beta/2)(\alpha_m + \alpha)}{\theta_b \cos(\alpha/2)(\beta_m + \beta)}}{\ln \dfrac{\sin(\beta/2)}{\sin(\alpha/2)}} \tag{5}$$

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[27] Shamos, *Great Experiments in Physics* (ref. 23), 64.

[28] Ibid., 64.

[29] See Martinez, "Coulomb's Torsion Balance Experiment" (ref. 9), 523-525 for derivation of this equation.

θ_a is the elastic modulus of the wire in a first trial, θ_b the elastic modulus of the wire in the subsequent trial, and generally $\theta = \mu D^4/l$. If we assume that the wire is not over-twisted, then $\theta_a = \theta_b$ (and thus they cancel each other out). Further, α is the separation angle between the two pith balls on a first trial, β the separation angle on a subsequent trial, α_m is the micrometer angle on a first trial, and β_m the micrometer angle on a subsequent trial. As can be seen from equation (5), we need two trials to calculate a possible exponent n. Thus, we can calculate that Coulomb's results predict an exponent of 1.98 for trials 1-2, an exponent of 1.84 for trials 2-3, and an average exponent of 1.91. (Later, we will discuss the likely illegitimacy of this averaging process). These results should be compared with the theoretical exponent value of 2 appearing in equation (1).

In order to evaluate the results of replications, we need to decide how they compare to the exponent predicted by Coulomb's results. In the following section we will analyze two recent replications of Coulomb's experiment, specifically with respect to how experimental outcomes compare to the exponent. The focus will be on Martinez's work (for Martinez has already thoroughly analyzed Heering's papers).

PREVIOUS REPLICATIONS: MARTINEZ AND HEERING

We will focus on three unresolved issues that will help us to convey the problems involved with replicating the experiment and how the experimental results compare to the exponent which Coulomb's own results predict. These three issues provide three parts of an answer to the question: What is the benefit (to historians of science) of replicating an experiment that has already been replicated in recent times?

The first issue involves establishing veracity. The two recent scholarly replications end with directly contradicting conclusions: Heering claims that he found it impossible to attain the results Coulomb reported in his 1785 memoir, while Martinez claims that such results are most likely typical.[30] Although Martinez discredits much of Heering's evidence, Martinez's analysis is not conclusive, so further study is warranted.

Secondly, both extant replications diverge from Coulomb's 1785 apparatus in ways that we believe to be significant. For example, Heering's replication included a copper wire (rather than silver) that was soldered to the micrometer (rather than clamped). Also, his needle was made out of PVC. Heering's replication may have failed because of these differences. In fact, the appendix to Martinez's 2006 paper appears to confirm this suspicion.[31] There, Martinez experimented with various wire compositions, such as aluminum. In one case, the wire was tied to the micrometer (again, rather than clamped), and in these experiments, Martinez produced results in line with those produced by Heering. But Martinez's own apparatus was likewise flawed in other respects. For the fourteen successful experiments that Martinez published in the body of his paper, the silver wire's thickness was nearly twice the thickness of the one Coulomb used in reporting his 1785 results. The needle Martinez used was made out of plastic; his attempts with a needle made from a combination of wax and synthesized shellac resulted in one "needle [that] sagged a bit too much and another [that] reacted to the charge of the pith balls."[32] In particular, he found that "the waxed needle itself accelerated toward the

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[30] Heering, "Coulomb's Inverse Square Law" (ref. 8), 990. Martinez, "Coulomb's Torsion Balance Experiment" (ref. 9), 547.

[31] Martinez, "Coulomb's Torsion Balance Experiment" (ref. 9), 547-561.

[32] Ibid., 536. Bracketed insertions added for clarity.

stationary ball when the two were close… and was interfering with the repulsion of the pith balls."[33] Martinez concluded that the material he used for his wax needles was not electrically neutral, so he used the plastic needles to avoid the issue. In the following section we demonstrate that Coulomb's needle, made from a combination of shellac and turpentine, very likely exhibited the source of error identified by Martinez, thereby making Martinez's use of plastic needles historically unfaithful. The behavior of the electric torsion balance is quite sensitive to its material composition. Hence, evaluating the success of Coulomb's particular rendition of the experiment is crucially dependent upon replicating *Coulomb's version* of the balance. We present such a replication (and its results) in the next section.

The third and final unresolved issue concerns the accuracy with which prior results were reported. Coulomb's 1785 results predict exponents of 1.98 and 1.84.[34] Thus, we label any set of trials that results in exponents $n = 2.00 \pm 0.16$ *successful* Coulomb experiments. Widening the interval a bit more, we label any experiments yielding $n = 2.00 \pm 0.50$ *moderately successful* Coulomb experiments.[35]

In Tables 1 and 2 respectively, we see the results of the recreations done by Heering and Martinez. Heering's published results include two successful experiments (of eleven), two moderately successful experiments, and seven unsuccessful

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[33] Ibid., 560.

[34] Coulomb, "Premier Mémoire sur l'Électricité" (ref. 1).

[35] Our "moderately successful" label excludes the "successful" experiments, even though the successful experiments are, strictly speaking, a subset of the moderately successful experiments.

experiments.[36] Martinez reports eleven (of eighteen) (≈61%) successful experiments, four moderately successful experiments, and one unsuccessful experiment.[37] Martinez's results appear to confirm that successful Coulomb experiments are typical. As will be shown, this cannot be the case. Our results do demonstrate that an able experimenter with a faithfully-constructed Coulomb torsion balance can achieve moderately successful Coulomb experiments. Nevertheless, Martinez's methods and typicality claim require scrutiny.

Table 1: Recreation by Heering

micrometer	0	20	40	60	80	100	130	160	200	250	300	360
separation	32.5	26	22.5	19	16	14.5	13	10.5	8	6.5	5.5	4

trials	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	11-12
exponent	1.52	2.10	1.36	1.11	1.78	2.03	0.81	0.72	1.01	1.04

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[36] Heering, "Coulomb's Experimental Proof" (ref. 9), 14. See also Heering, "Replication of Torsion Balance Experiment" (ref. 9), 55.

[37] Martinez's unsuccessful experiment can be explained by taking into account the error introduced when he twisted the wire beyond its linearity range prior to experiment B2.

trials	11-12
exponent	0.54

Table 1. *An example of data from Heering's replication, including micrometer and separation angles, with corresponding calculated exponents for every two consecutive trials. Sources: Heering, "Coulomb's Experimental Proof" (ref. 9) and Heering, "Replication of Torsion Balance Experiment" (ref. 9).*

Table 2: Recreation by Martinez

experiment #	A1	A2	A3	A4	B1	B2	B3	B4	B5
exponent reported	1.894	1.956	2.277	2.068	2.216	2.707	1.678	2.357	2.266

experiment #	C1	C2	C3	D1	D2	D3	D4	D5	D6
exponent reported	1.911	2.025	2.072	1.679	1.956	1.878	1.919	2.069	2.072

Table 2. *A set of fourteen of Martinez's published experiments (not including his appendix section) with their corresponding average exponent. Source: Martinez, "Coulomb's Torsion Balance Experiment" (ref. 9).*

The exponents that Martinez reports are *average* exponents of an experimental run.[38] Table 3 presents a list of exponents calculated for *each* of Martinez's consecutive trials (i.e., for every two consecutive measurements, as he himself did before averaging them). Note that now only eighteen of forty-three (≈42%) trials can be considered successful Coulomb experiments. Moreover, if one takes into account that before performing the set of the fourteen experiments (corresponding to forty-three trials) published in his paper, Martinez performed over sixty experimental trials (published in appendix part his paper), most of which resulted in unsuccessful exponents, it becomes far from obvious that his data truly does confirm that Coulomb-type results are *typical*.

Table 3: Martinez's Consecutive Trials

experiment #	A1		A2		A3		A4		B1	
exponent	2.11	1.67	2.26	1.64	2.44	2.10	2.31	1.81	2.56	2.15

experiment #	(con. B1)	B2			B3			B4		B5

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[38] An 'experiment' or 'experimental run,' such as A1, consists of three to four 'measurements' or 'trials' with corresponding two or three predicted exponents.

exponent	1.92	2.76	2.72	2.62	1.81	1.54	2.43	2.43	2.28	2.40
experiment #	(con. B5)	C1		C2		C3		D1		
exponent	2.12	2.22	1.59	2.30	1.74	2.27	1.86	2.03	1.64	1.35
experiment #	D2			D3			D4			D5
exponent	2.10	1.92	1.83	1.87	1.85	1.90	1.99	1.88	1.87	2.00
experiment #	(con. D5)	D6								
exponent	2.13	2.40	2.12							

Table 3. *Martinez's complete published experiments (not including his appendix section) along with forty-three exponents corresponding to any two consecutive measurements in an experimental run. Source: Martinez, "Coulomb's Torsion Balance Experiment" (ref. 9).*

The legitimacy of an experimental design includes not only attaining certain results, but also being able to explain, at least to some extent, those results that diverge from the expected values through error sources. Martinez himself does exactly this when he states that the "likely cause of such unusually high exponents [as reported in experiments B1, B2, B4, and B5 in Table 2] was that once the silver wire had been subjected to a large total torsion [in experiments A3 and A4], the wire's elastic modulus decreased," resulting in higher exponents.[39] However, when we look at the *specific* exponents of the experimental trials of experiments B1, B2, B4, and B5 (as portrayed in Table 3), rather than at the *average* exponents, we notice that there are numerous experimental trials that give Coulomb-type results including 1.92 and 2.12, as well as moderately successful results, including 2.15, 2.43, 2.28, and 2.40. So Martinez's explanation of higher exponents fails once we ignore the average exponents and look at each exponent calculated per trial.

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[39] Martinez, "Coulomb's Torsion Balance Experiment" (ref. 9), 543. Portions in brackets added for clarity.

Hence, we are left with the conclusion that only when averaging them do Martinez's results support the claim that Coulomb's data was typical and that the torsion balance experiment behaves in a non-erratic manner (i.e., high or low exponents can be explained by taking the appropriate error source into account).[40]

OUR REPLICATION OF COULOMB'S EXPERIMENT

In this section, we discuss those aspects of our replication of Coulomb's torsion balance that diverge from recent replications by Heering and Martinez. Our data is discussed in short sets, in the spirit of Coulomb's 1785 memoir.

Our presentation comes in two parts. First, we describe our experience in performing the torsion balance experiment with various historically-accurate replicas of the needle, which generates the unavoidable error source we have identified. Second, we will discuss our corresponding hypotheses: 1) the success of the torsion balance experiment is highly dependent on the materials involved, and 2) it degenerates when parameters are altered.[41]

Shellac Versus Plastic

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[40] Whether Coulomb would consider Martinez's averaging technique to be a legitimate manner by which to demonstrate the electrostatic law is an interesting question that merits further study. A first glance at Coulomb's various memoirs suggest that he does not make use of averaging techniques. It seems that averaging calculated exponents from measured trials, as Martinez does, is an anachronistic manner by which to judge the success or failure of Coulomb's experiment.

[41] A large majority of our results, including the results presented here, were recorded with a high quality digital video camera and can be accessed at http://www.exphps.org/index_files/Page446.htm.

The chronology of our replication of Coulomb’s torsion balance somewhat mimicked that of Martinez. (See Figure 2 for images of our apparatus). In the beginning we attained data that yielded exponents that ranged from 0.5 to 2.5, in a relatively erratic manner, but with time, as our experimental techniques matured, we were able to attain consistent results that were moderately successful. Unsuccessful results were explained by various sources of error, such as charge loss (lower exponent) and over-twisting of the silver wire resulting in a modification of its elastic modulus (higher exponent). We refer the reader to Table 4 for a comparison of various dimensions of the torsion balance apparatus as reported in Coulomb’s 1785 memoir, Martnez’s 2006 replication, and our recent replication.[42]

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[42] Martinez presents a similar table (Martinez, “Coulomb’s Torsion Balance Experiment” (ref. 9), 537). The results reported for Coulomb’s 1785 memoir are taken directly from Martinez’s work and were corroborated through reading Coulomb’s 1785 memoir. (We did not recalculate Martinez’s approximation of the diameters of the sliver wire or the pith balls.)

Figure 2. The equipment used in our replication of Coulomb's torsion balance experiment. Left: the complete balance. Right: detail of the micrometer and the clamp holding the silver wire.

Table 4: Parameters and Measurements of Each Apparatus

Components	Coulomb	Martinez	Shech and Hatleback
glass cylinder, diameter	32.48cm	30.0cm	29.8cm
glass cylinder, height	32.48cm	30.0cm	29.8cm
apertures on lid, diameter	4.51cm	3.1cm	3.3cm
glass tube, length	64.97cm	61.5cm	61.5cm
silver wire, length	75.79cm	75.5cm	75.0cm
silver wire, diameter	0.035mm	0.051mm	0.051/0.031mm+
needle, length	21.66cm	20.5cm	20.3-25.0cm*
pith balls, diameter	4.5 to 6.8mm	6mm	5-6mm

* The Spanish-wax needle was 25cm, the plastic needle was 20.3cm and the shellac needle was 21cm.

\+ The experiments with the Spanish-wax and Plastic needles were conducted with a silver wire of 0.051mm and the experiments with the Shellac needles were conducted with a silver wire of 0.031mm.

Table 4. *Comparison of dimensions of torsion balances. Sources: Martinez, "Coulomb's Torsion Balance Experiment" (ref. 9) and Coulomb, "Premier Mémoire sur l'Électricité" (ref. 1).*

We were able to acquire wax that was most likely quite similar to Coulomb's Spanish wax: our wax's main compound was shellac (not synthesized plastic) along with turpentine and other colorants. We managed to make very thin needles, weighing only 0.2-0.3 grams, by melting the wax on electric burner covered in aluminum foil and dipping a thin thread of silk into the wax.[43] Even still, in our most successful replications (in which we used a silver wire of thickness 0.051mm, as Martinez did), we were able only to attain exponents that ranged between 1.6-1.8 (within the *moderately successful* range). We were unable to push the exponent closer to the successful range. Table 5 presents an example of such data. In addition to calculating the exponents predicted by our measurements, we present exponents that were fixed for maximal charge loss effects. That is, we assumed that the entire charge loss in the experiment, 0.5 degrees, was lost between consecutive trials, and we recalculated the exponent appropriately.

Table 5: Results with Spanish Wax Needle (Shech and Hatleback)

experiment #	S1			S2		
micrometer	5	90	180	5	90	180
separation	45	28	20.5	42.5	25	18
total deg. lost			0.5			0.5
trial	1-2	2-3	*Ave.*	1-2	2-3	*Ave.*
exponent	1.76	1.68	1.72	1.62	1.63	1.63
*fix**	1.84	1.83	1.83	1.69	1.79	1.74

** Accommodating charge loss, maximal effect assumed*

+ wire diameter: 0.051mm   needle used: Spanish-wax   needle weight: 0.3g

Table 5. *Two experiments from our replication with 0.051mm silver wire and Spanish wax needle.+ The table includes: micrometer angles and separations angles for each measurement, total degrees lost due to charge loss in an experimental run, calculated exponents for each two consecutive trials in an experimental run, and corresponding exponents fixed for maximum charge loss.*

Furthermore, even from those exponents fixed for maximal charge loss, only one exponent borders the successful threshold of 1.84. Of course, maximal charge loss is unrealistic, since charge is lost over the entire set of measures, not just (for instance) between trials 1-2. So charge loss could not explain our low exponents.

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[43] This process took weeks to master because it is very difficult to create a thin and light needle that is approximately homogenous.

Since the experimental results were consistent, and our apparatus very similar to Coulomb's and Martinez's, we decided to study the needle further. In doing so, we found that our shellac needle seemed to be rather strongly attracted by the charged stationary pith ball.[44]

There are several noteworthy aspects of the phenomenon that we witnessed. (i) We managed to attract the needle inwards from separation angles as large as 45 degrees by placing a charge on the stationary pith ball. (ii) The strength by which the needle was pulled seemed to be roughly proportional to the charge placed on the stationary pith ball and approximately inversely proportional to the separation angle between the two pith balls. (iii) The needle, with no pith ball, would stick to the stationary charged pith ball for up to thirty minutes. Thus, it could not be the case that our needle was charged or conductive, for in such cases, the charge on the tip of the needle would equilibrate with that of the stationary pith ball and the two would repulse each other (which did not happen). Furthermore, if the needle were conductive, the charge would evaporate quickly through the silver wire (more quickly than it would without contact with the needle), and this was not witnessed.[45]

Thus, we concluded that the Spanish-wax needle is a dielectric material. All dielectric materials electrically polarize in the presence of an electric field. The strength of polarization depends on the electric field (the charge placed on the stationary pith ball) and a constant characteristic of the material (the electric susceptibility). Our Spanish-

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[44] Our best needle did not sag, and it did not behave erratically.

[45] In effort to confirm that the needle was not conductive, we attempted to run large quantities of electricity through the needle with a Whimshurst machine, which the needle did not conduct.

wax needle, unlike Martinez's plastic needle but like his (synthesized) wax needle, portrayed a strong polarization phenomenon that accounts for our lower exponents. In addition, notice that once one takes the polarization phenomena into account, one can better explain the lower exponent of 1.84 which Coulomb attained for his trials 2-3 (since, according to Coulomb, charge loss in his experiment did not contribute significantly).

In order to test our reasoning, we decided to run some experiments with a plastic needle. We originally used a heavy, short plastic needle made out of a Starbuck's coffee stirrer (plastic). However, this needle behaved erratically, so we attempted (unsuccessfully) to make needles from Gillette razor handles as Martinez did. Eventually, we managed to make a light, thin needle from a white plastic stirrer. Table 6 provides a sample of the results of experiments run with this needle. We found that the plastic needle barely exhibited the polarization phenomenon; it only did so significantly at small angles less than 8 degrees. Further, as can be seen in from Table 6, we did attain successful exponents of the type Martinez described. In fact, we found that we were able to perform the torsion balance experiment with just the plastic needle and no pith ball. The needle's tip picked up charge, but the needle itself did not conduct. The extra bit of charge picked up by the needle, which is not distributed spherically, might explain the high exponent we found in trails 1-2 in experiments P1 and P2. This issue calls for further study.

Table 6: Results with Plastic Needle (Shech and Hatleback)

experiment #	P1			P2		
micrometer	5	90	180	5	90	180
separation	44	30	23	38	25	19
total deg. lost			0.5			0.5
trial	1-2	2-3	*Ave.*	1-2	2-3	*Ave.*

exponent	2.31	1.95	2.13	2.33	1.98	2.15
*fix**	2.43	2.14	2.28	2.46	2.20	2.33

** Accommodating charge loss, maximal effect assumed*

+*wire diameter: 0.051mm   needle used: Plastic   needle weight: 0.3g*

Table 6. *Two exemplary experiments from our replication with 0.051mm silver wire and plastic needle.+ The table includes: micrometer angles and separations angles for each measurement, total degrees lost due to charge loss in an experimental run, calculated exponents for each two consecutive trials in an experimental run, and corresponding exponents fixed for maximum charge loss.*

The important result is that the experiment's success is highly dependent on the materials used. In order to confirm our hypothesis (that shellac portrays a strong polarization effect), we ordered several different kinds of shellac and made various different shellac needles.[46] All such needles portrayed similar polarization effects to those witnessed with the Spanish-wax needle. Ultimately, we conclude that it is highly likely that Coulomb's own needles were closer in material composition to our Spanish-wax and shellac needles than to Martinez's plastic needles.

In addition, we ran experiments with our best shellac needle and with a new 0.035mm-diameter silver wire, matching Coulomb's 1785 wire. Table 7 shows the results, which are similar to those attained with the Spanish wax needle. All eight exponents indicate moderately successful experiments. Once we fix for maximal charge loss, all results fall within the 1.6-1.83 range. Accordingly, we suggest that after running sets of experiments that ranged in exponents between 1.6 and 2.0 (due to various sources of error), Coulomb chose to publish those data points that best demonstrate the fundamental electrostatic law and exemplify the application of his torsion balance.

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[46] Our shellac, ordered from www.shellac.net, is not synthesized or heavily processed and includes shellac of the following types: Kusmi See, Dark Seed, Kusmi #1 Button, Kusmi #2 Button, Bysakhi Button, Gossamer Flake, Hand Made Yellow, and Lemon Yellow Orange.

Table 7: Results with Shellac Needle and Coulomb-Faithful Wire (Shech and Hatleback)

experiment #	E1			E2		
micrometer	0	90	180	0	90	180
separation	35.5	18.5	13	27	13	9
total deg. lost			0.5			0.5
trial	1-2	2-3	*Ave.*	1-2	2-3	*Ave.*
exponent	1.75	1.62	1.68	1.62	1.50	1.73
*fix**	1.83	1.82	1.82	1.71	1.77	1.74

** Accommodating charge loss, maximal effect assumed*

+ wire diameter: 0.035mm needle used: Shellac needle weight: 0.2 grams
humidity: 47-54% temp.: 74-78° F

experiment #	E3			E4		
micrometer	0	90	400	0	90	400
separation	40	22	9.5	41.5	23	10
total deg. lost			0.5			0.5
trial	1-2	2-3	*Ave.*	1-2	2-3	*Ave.*
exponent	1.68	1.53	1.59	1.66	1.53	1.59
*fix**	1.76	1.63	1.69	1.73	1.63	1.68

** Accommodating charge loss, maximal effect assumed*

+ wire diameter: 0.035mm needle used: Shellac needle weight: 0.2 grams
humidity: 47-54% temp.: 74-78° F

Table 7. *Four exemplary experiments from our replication with 0.035mm silver wire and shellac needle.+ The table includes: micrometer angles and separations angles for each measurement, total degrees lost due to charge loss in an experimental run, calculated exponents for each two consecutive trials in an experimental run, and corresponding exponents fixed for maximum charge loss.*

Sensitivity to Materials and Parameters

Our hypothesis that the success of the torsion balance experiment is highly dependent upon its material makeup is partially confirmed by prior replications. Divergence from Coulomb's original setup results in an apparatus that does not supply successful Coulomb experiments. The success of the experiment, we submit, depends on the wire material that is used, on the manner in which the wire is attached to the micrometer, and more generally on the dimensions of the apparatus. We further strengthen this hypothesis with the experimental data presented in the previous subsection regarding the needle.

In addition, the apparatus is very sensitive to extreme separation angles. We found that separation angles smaller than 10 degrees, resulting from a very small amount of charge, or from over-twisting the micrometer so as to force the pith balls close together, afford lower exponents. In such a situation, the force between the pith balls is weakened. Thus, as the separation angle decreases into the region of very low angles, the experiment degenerates. Large separation angles and large micrometer angles modify the wire's elastic modulus, thereby preventing successful experiments. We add that it becomes impossible to run the experiment with large separation angles, since the amount of charge necessary to produce angles larger than approximately 60 degrees repulses the pith balls from each other so violently that the needle flies outward and either bumps into the stationary ball or, if the latter is quickly removed, over-twists the wire. One can counter this effect by using a thicker wire or by beginning the experiment with large micrometer torsion, but both of these techniques result in unsuccessful experiments, since the large torsion force overpowers the electrostatic force quickly as charge is being lost.

Achieving success becomes a matter of discerning which torsion balance (which materials, dimensions, and variables) is appropriate for the phenomenon being investigated (whether it is fluid resistance, repulsive electric forces, attractive electric forces, magnetic forces, and so on). Hence, we are left with the following question: if, in order to demonstrate the electrostatic law, Coulomb needed to choose the 'correct' torsion balance, by which criteria could he have made such a crucial choice? We speculate that a large part of the answer to this question involves the experimenter's abilities to identify sources of error and have a theoretical story to tell about why experiments degenerate in the manner they do.

COULOMB AND THE ELECTRIC POLARIZATION OF THE NEEDLE

Our study of the torsion balance thus leads us to the historical circumstances involved with Coulomb's awareness of sources of error. Specifically, we wonder whether Coulomb observed the needle's polarization phenomenon and, if so, how he dealt with this error source. A detailed answer to this question entails examination of the entirety of Coulomb's memoirs. We presently have space to take only preliminary steps toward this end by focusing on Coulomb's first and third memoirs on electricity and magnetism.

In short, we do not think that Coulomb observed the needle's electric polarization effect without a pith ball, nor did he realize that this was a source of significant error.[47] Even though Coulomb's 1785 memoir includes remarks detailing sources of error that Coulomb took to be significant, there is no mention there of the polarization phenomenon. Moreover, not all of the error sources that Coulomb mentions were applicable to his particular rendition of the experiment, though he found it appropriate to discuss them, since they might be potentially significant for a replication of the experiment. He explicitly mentions that when error sources become significant, they must be corrected for.[48] The error sources identified by Coulomb include charge loss due to contact with air over time, small angle approximations, and exceeding the wire's torsion limit by over-twisting it, but the polarization phenomenon is not mentioned.[49]

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[47] "Source of significant error" here means that the chance for successful experimentation is severely impaired by the error source.

[48] Coulomb, "Premier Mémoire sur l'Électricité" (ref. 1), 575-576.

[49] Ibid., 574-577.

Coulomb certainly was aware of the common phenomenon of static electricity, which had become a popular subject in the eighteenth century, and he was aware that conductors, after being grounded, react to electrically charged bodies. For example, in his second memoir on electricity and magnetism, when discussing possible sources of experimental error, he explicitly states that when performing torsion balance experiments one must "distance all conductive bodies at least three feet from the electrified globe and the needle."[50] Yet he makes no mention of the effects that dielectric bodies might have on the experiment.

In order to investigate further whether Coulomb knew of the needle's polarization phenomenon, we look to his third memoir on electricity and magnetism, which is particularly relevant to our recreation of the torsion balance experiment for two reasons.[51] First, Coulomb announces that the entirety of experiments in the third memoir are conducted with the same type of electric torsion balance described in his first memoir, and he even repeats a description of the apparatus and experiment.[52] In this sense, the third memoir allows scholars to investigate additional experiments conducted with the electric torsion balance with corresponding extra data. For instance, one can extract an additional data point (an exponent of 1.97) from two reported experimental trials conducted with the torsion balance.[53]

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[50] Coulomb, "Second Mémoire sur l'Électricité" (ref. 2), 586.

[51] C.A. Coulomb, "Troisième Mémoire sur l'Électricité et le Magnétisme. De la quantité d'électricité qu'un corps isolé perd dans un temps donné, soit par le contact de l'air plus ou moins humide, soit le long des soutiens plus ou moins idioélectriques," *Mémoires de l'Académie Royale des Sciences* (1788): 616-638.

[52] Ibid., 616-617.

[53] Ibid., 617.

The second reason for the third memoir's significance is that it is wholly devoted to the study of charge loss in conductors in contact with air and dielectric material. So, for example, Coulomb describes how, in searching for the best insulator to study charge loss of conductors due to surrounding air, he experimented with various needles and chose the shellac needle as the best insulator.[54] This is strong evidence that Coulomb did not witness (or, at the very least, did not *notice*) the polarization phenomenon. If he had, surely he would have mentioned it in this third memoir.

In fact, Coulomb knew that the presence of dielectric material between conductive bodies diminishes the electric force between the two. But he believed that the cause for such behavior was either that no perfect dielectric existed or that the surface of dielectric materials might conduct electricity if they were covered with conducting water or gas molecules. This second cause is one of the reasons Coulomb made thin needles: to minimize surface area and, thus, to maximize insulation.[55] Yet at no point in the memoir, which describes in detail charge loss in conductors in contact with dielectric material, does Coulomb mention the idea that, even with a near-perfect insulator with no charge leakage across its surface, such an insulator will react to an electric field in the way that matches what we witnessed. Coulomb appears to have no conception of *electric* molecular polarization; instead, he envisages *magnetic* molecular polarization. Coulomb's biographer Gillmor notes that as early as 1777, and certainly by 1787, Coulomb thought that magnets were composed of small particles which themselves acted

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[54] Ibid., 615.

[55] Ibid., 612-614.

as small magnets.[56] Furthermore, Gillmor notes that, in his later memoirs, Coulomb states that he planned to study the distribution of electricity within the body of dielectrics — a study that might have informed him of electric polarization — but such work was never published.[57]

Of course, it is altogether possible that Coulomb noticed the polarization phenomenon — due to imperfect insulation and, more importantly, due to conducting water/gas molecules on the surface of the dielectric — but ultimately regarded it as an insignificant source of error. However, given the stark impact that the effect has on the experiment, it is exceedingly unlikely that Coulomb identified the source of error but dismissed it as negligible. A more comprehensive study of Coulomb's works would most likely shed light on this issue.

CONCLUSION

In contrast to Heering's research and in agreement with Martinez's work, our replication confirms that it is possible to accurately recreate Coulomb's experiment as he described it and, in doing so, to obtain results in the *moderately successful* category (exponents of 1.5-2.0). The best data, where error sources are minimized, suggests exponents of 1.6-1.8, still within the moderately successful range. In contrast to Martinez, we suggest that Coulomb's reported results are not typical. We found it

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[56] See Gillmor, *Evolution of Physics and Engineering* (ref. 2), 181, where Gillmor conveys Coulomb's claim that "each point of a magnet or of a magnetized bar can be regarded as the pole of a tiny magnet…"

[57] Ibid., 206.

exceedingly difficult to attain data that were as close to the theoretically-predicted value as the results that Coulomb reported. We suggest that the reason for such difficulty is that shellac-based needles exhibit a strong electric polarization phenomenon to which plastic needles, such as Martinez's, are not susceptible. In fact, even Martinez's published data is undermined once we reject the averaging technique he used to analyze his data. Moreover, we found that the experimental success of the torsion balance is highly dependent on the materials involved and that the experiment degenerates quickly owing to the construction materials of the apparatus and the alteration of certain parameters.

Further, when looking at Coulomb's memoirs, we find no evidence supporting the idea that Coulomb was aware that a perfectly insulating dielectric, with almost no conductive molecules surrounding its surface area, causes the electric force between two electrified bodies to decrease significantly in the manner that the shellac needles do in the torsion balance experiment. We submit that this issue calls for further scrutiny.

In sum, two centuries after Coulomb, we must conclude that Coulomb's electric torsion balance experiment, as designed, has not yet been successfully replicated, and that we must keep learning from twisting wires and melting shellac.