Replicating Mathematical Inventions: Galileo's Compass, Its Instructions, Its Students

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Questions about how closure is achieved in disputes involving new observational or experimental claims have highlighted the role of bodily knowledge possibly irreducible to written experimental protocols and instructions how to build and operate instruments. This essay asks similar questions about a scenario that is both related and significantly different: the replication of an invention, not of an observation or the instrument through which it produced. Furthermore, the machine considered here—Galileo's compass or sector—was not a typical industrial invention (like a spinning jenny), but a mathematical invention (a calculator), that is, a machine that produces numbers, not yarn. This case study describes some of the similarities and differences between replicating experiments, traditional machines producing material outputs, and mathematical inventions yielding calculations or information. This comparison indicates that, as in other kinds of replication, the replication of mathematical inventions involves texts (the calculator's instructions) but that in this case bodily knowledge cannot be properly described as either tacit or explicit. It rather takes the shape of memory—muscle memory—that may be recalled from reading the instructions.

Questions about the process through which closure is achieved in disputes involving new observational or experimental claims have highlighted the key role of bodily and possibly tacit knowledge deemed to be irreducible to written experimental protocols or instructions about how to build and operate instruments. (Collins 2010). This essay asks some of the same questions about a scenario that is related but significantly different: the replication of an invention, not of an observation and/or the instrument through which it produced. Furthermore, the machine considered here, Galileo's compass or sector, was not a typical industrial invention (like,

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say, a spinning jenny), but a mathematical invention (a calculator), that is, a machine that produces numbers, not yarn. To put it in Jim Bennett's terms, I analyze the specific problems posed by the replication of mathematical instruments (which yield calculations), not philosophical ones (which yield physical effects) (Bennet 1986, pp. 1–28).

Replication means something rather specific in cases like Galileo's compass where knowledge and property are intertwined, where discussions of a third party's ability to use and reproduce an instrument were inextricably tied to determining not only what the invention was, but who owned it. (Although no patent was actually involved, this controversy was framed by the logic of patent law and the customs of inventors as reflected in that law). Experimental replications are epistemological affairs, the focus being on the reproduction of instruments and the claims they produced. That kind of replication did apply to Galileo's compass, whose copies were made to reliably reproduce the same calculations. In addition to that, however, the fact that the inventor could disseminate functioning copies of an invention was seen as conclusive evidence that the inventor "possessed" the invention precisely because s/he could transfer it—alienability being a crucial element of the definition of property. Being able to have somebody else use the invention meant that the invention was not just a stable material entity reliably producing the same effects but was also, at the same time and for the same reasons, a stable object of property. The construction of an object as stable is a condition of possibility to both experimental replications and to the transfer of inventions but, as I hope to show, the parameters of that construction overlap only partially.

Another significant difference between the dissemination of Galileo's calculator and the replication of observational or experimental claims is that the actors whose replication mattered the most were not what Harry Collins has called the "core set" of authoritative scientists in a given field, or the members of the Royal Society who witnessed and certified Boyle's experiment, but rather the students, many of them unnamed, who bought the compass from Galileo and paid him to teach them how to use the instrument. Their ability to learn from Galileo and remember how to set up and operate the compass to make it perform its operations played a fundamental role in settling a bitter controversy about the identity and inventorship of the instrument. Bodily knowledge alone, however, was not enough to secure the replication of the compass. Texts were as important in this controversy as they are in scientific controversies, except that they belonged to the humble and much understudied genre of the instruction manual that taught, or rather reminded, users how to operate the device. Finally, textuality played another distinctive role in this case that—quite surprisingly—was eventually litigated as a dispute regarding book plagiarism rather than the appropriation of an invention. The boundary between text and machine was a porous one, necessarily so, largely because of the ways in which the compass performed its calculations.

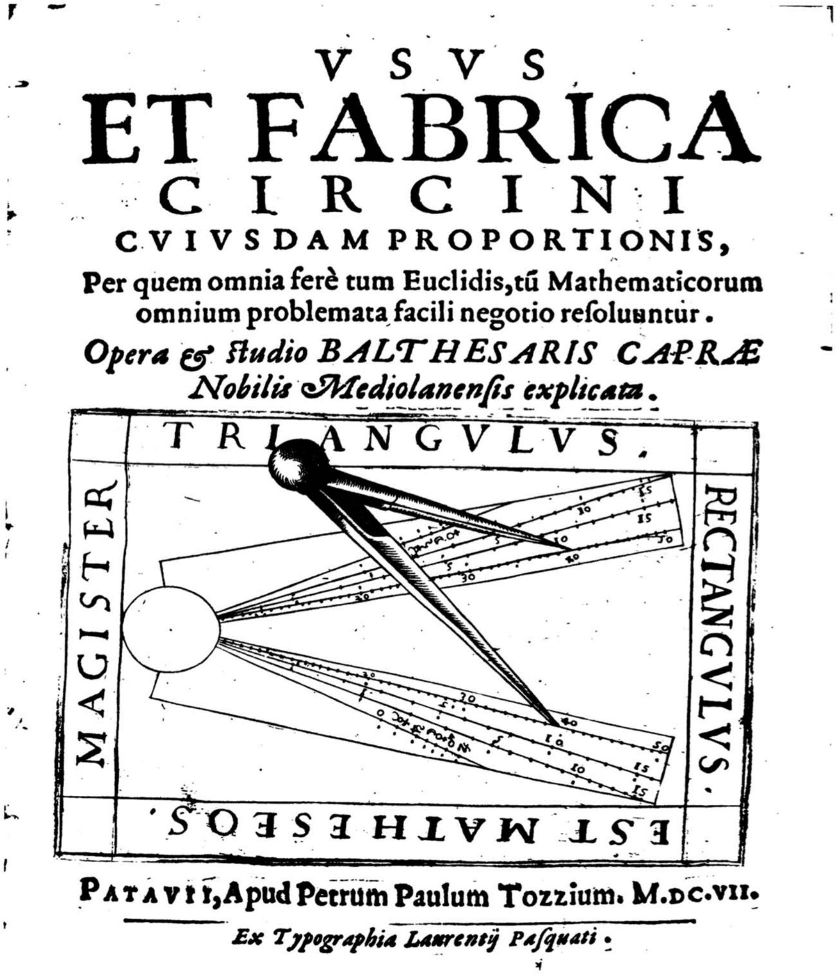
These and other features that will be discussed in a moment indicate that there was something rather specific, perhaps unique, to the replication of mathematical inventions, especially calculating instruments, as they straddle the lines between objects of knowledge, knowledge-making objects, and saleable goods. The tense relationship between computer algorithms and modern intellectual property law suggests that those difficulties may have mutated in time but have surely not disappeared (Samuelson et al. 1994, p. 2320; Sherman 2019; Diaz 2019).

Between Descriptions and Instructions

In 1606, while teaching at the University of Padua, Galileo printed the *Le operazioni del compasso geometrico et militare* (1606).[1] It was a short book describing the use of a multi-purpose sector or "compass" that enabled mathematically unskilled users to perform a wide range of commercial tasks (currency exchange, compound interest, etc.) as well as ballistic calculations like the so-called problem of caliber: starting with the charge of powder known to be right for a certain shot with a cannon of a given bore and a ball of a given material (say, stone), calculate the charge of powder to be used for the same shot with the same cannon, but with a cannonball of a different material (say, iron) (Heilbron 2010, pp. 100–2). Different sets of lines laid out on the two hinged flat legs of the instrument enabled different types of calculations, with the help of an additional divider (Fig. 1). Fitted with a brass appendix, the sector could also function as a *squadra*, a popular instrument among artillerymen (Fig. 2). Useful to merchants, bankers, land-surveyors, military engineers, and gunners, Galileo's compass was probably the most versatile and sophisticated calculator available at that time.[2]

1. Galilei, Galileo. 1606. Reprinted in Galilei, Galileo. 1890–1909, Vol. II, pp. 365–424. This summary of the events of the dispute is based on Stillman Drake (1976); Antonio Favaro (1907–8); Stillman Drake (1978); Silvio Bedini (1967). A more complex perspective is in Roberto Vergara Caffarelli (1992). Noteworthy among the recent literature are Matteo Valleriani 2010, pp. 27–38; Nick Wilding 2014, pp. 38–49; John Heilbron 2010, pp. 100–104. An overview of the history of the sector and its varieties, see Michael Williams and Erwin Tomash (2003).

2. For the background to Galileo's development of his compass, and the similarities and differences between Galileo's instrument and other sectors available at the time see Paul Lawrence Rose (1968); Filippo Camerota (2000); Stillman Drake (1977); Alex Marr (2011).



VSVS
ET FABRICA
CIRCINI
CVIVSDAM PROPORTIONIS,
Per quem omnia ferè tum Euclidis, tũ Mathematicorum omnium problemata facili negotio resoluuntur.
Opera & studio BALTHESARIS CAPRÆ Nobilis Mediolanensis explicata.

PATAVII, Apud Petrum Paulum Tozzium. M.DC.VII.
Ex Typographia Laurentij Pasquati.

Figure 1. The compass as illustrated by Capra, showing the use of the divider.

The compass, Galileo argued, showed that it was not inappropriate for the tyrant of Syracuse to have asked Archimedes if there was an easy way to learn mathematics (Galilei 1890–1909, vol. II, p.369). Many centuries later, Galileo had proven that there was indeed a royal road to mathematics, a mechanical one that, like modern computers, allowed people to perform

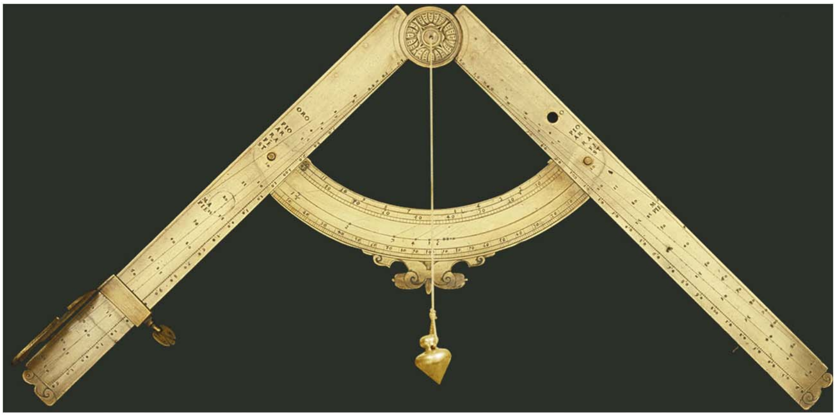


Figure 2. Galileo's compass set up as a gunner's *squadra*. Image used with permission of the Collection of Historical Scientific Instruments, Harvard University.

operations without understanding them[3] (Favaro 1891, p. 369). The delivery of streamlined mathematical enlightenment to the young aristocrats he tutored was not the book's sole goal, however (Galilei 1890–1909, vol. II, p. 370). Galileo claimed that he had decided to publish the *Operazioni* after hearing that someone was "preparing himself to appropriate" the instrument:

> [This] put me in need to secure, with the testimony of print, both my works and the disrepute of he who might appropriate them. It is the case that, as far as my protection is concerned,[4] I am not short of testimonies of Princes and other great Gentlemen who, since 8 years ago, have seen this instrument, and from me have been taught how to use it. It will suffice to mention only four of them. One was [...] the Prince of Alsace, [...] the Archduke of Austria, [...] the Landgraf of Hesse, [...] and the Duke of Mantua.[5] (Galilei 1890–1909, vol. II, p. 370)

3. "[D]esiderando che non restino per la difficolta' e lunghezza delle communi strade privi di cognizioni tanto a' nobili Signori necessarie, mi rivolsi tentare di aprire questa via veramente regia, la quale con l'aiuto di questo mio Compasso in pochissimi giorni insegna tutto quello che la geometria e l'aritmetica, per l'uso civile e militare, non senza lunghissimi studii per le vie ordinarie si riceve ..." Galilei 1890–1909, vol. II, p. 369.

4. Galileo used the now-archaic expression "far cauto," which, taken literally, would mean "to make cautious," but in fact meant "to assure" or "to give assurance" (Percolla 1889, p. 150).

5. The instruments for the Archduke and Landgraf were made of silver and are no longer extant, while the Duke of Mantua's brass compass is now in the Collection of Historical Instruments at Harvard. Mazzoleni's April 1607 affidavit mentions the two silver

Luckily for Galileo, he already had a text he could quickly take to the printer and publish as the *Operazioni*: the manuscript instructions manual he had been selling to the students who took classes with him on how to use the compass. Over the years, a scribe produced copies of the text as needed.[6]

Notice that while stating to have mobilized the "testimony of print" to secure his claim to the compass and make sure that those who planned to plagiarize him would be exposed for what they were if they pursued their devious plans, Galileo also added that the recognition of his inventorship was already safely established by the numerous testimonies of his students.[7] Setting aside for a moment the apparent tension between mobilizing the "testimony of print" while also stating that his students provided conclusive evidence of his inventorship, the book did not prove to be the effective deterrent he expected it to be. About a year later, Galileo was bringing an action against Baldassarre Capra in the *Riformatori* court in Venice, accusing him of having plagiarized the *Operazioni* in his own book on the compass: Capra's 1607 *Usus et fabrica circini*.[8]

During the proceedings, he repeated that his inventorship of the compass was established by the fact that, over an arc of ten years, he had "conferred and communicated" it to "very many Gentlemen and great Princes from various countries," well before he decided to print the *Operazioni* (Galilei 1890–1909, vol. II, p. 539). The same point was made in the opening section of his *Difesa* (Galilei 1890–1909, vol. II, p. 518), the book

compasses and their recipients (Galilei 1890–1909, Vol. II, p. 535). Galileo promised more silver compasses to the Medici (Galilei 1890–1909, Vol. X, p. 149) but it seems that by that time the compasses were produced in Florence by Medici artisans (probably by a Maestro Raffaello, Galilei 1890–1909, Vol. X, p. 157) and then sent to Galileo for delineation (Galilei 1890–1909, Vol. X, pp. 155–7). On the negotiations between Galileo and the Gonzaga see Galilei 1890–1909, Vol. X, pp. 106–7.

6. The bills of Galileo's scribe, Messer Silvestro, are reproduced in Galilei 1890–1909, Vol. XIX, pp. 166–7.

7. He would repeat those two points in Galilei 1890–1909, Vol. X, pp. 171–2, in his official complaint to the *Riformatori*.

8. Consisting of three officials, the *Riformatori dello Studio di Padua* was a committee of the Venetian Senate that oversaw both the University of Padua and all aspects of the book publishing business in Venice. Among other things, the *Riformatori* were in charge of the university staff (both the number and fields of teaching positions, and the scholars to fill them), the curriculum, and the course catalogue. Concerning the publishing business, they oversaw book licensing, book importation, as well as the Library of St Mark (Andrea Da Mosto, *L'Archivio di Stato di Venezia, Vol. 1* (Roma: Biblioteca d'Arte Editrice, 1937), pp. 216–18. Their control of the press was rather granular, down to the appointment of official proof-readers (Horatio Brown, *The Venetian Printing Press* (New York: Putnam's Sons, 1891), p. 175).

chronicling the dispute that Galileo published shortly after the trial, and elsewhere in that text:

> Ten years ago I started to have these Instruments made, and every year I have communicated and shared them with Gentlemen of various nations [… where] few or many of these Compasses of mine can now be found, brought there by the Gentlemen who received them from me together with their instructions, both oral and written. (Galilei 1890–1909, vol. II, p. 533)

The same language appears, virtually verbatim, in the previous paragraph[9] (Galilei 1890–1909, vol. II, p. 533). It is important to notice that Galileo did not simply invoke prestigious witnesses as credible people who could testify to the fact that he had his instrument by a certain date, but as people to whom he had taught how the compass worked. Taken together, these statements indicate that Galileo took the crucial evidence of his inventorship of the compass to be embodied rather than textual, instilled in the mind and hands of his students over almost ten years, and confirmed by the students' testimonies (introduced as evidence at the trial) that they materially received the compass and training directly from him. Still, as we will see, the embodied evidence of inventorship could only be conclusive if intersected with the textual evidence provided by the *Operazioni*.

In connecting inventorship to the ability to teach and transfer the invention, Galileo was adopting the legal definition of inventorship common at the time; a definition he was familiar with having applied for and received a Venetian patent for a water pump a few years earlier (Biagioli 2006a, pp. 1129–72). To receive a patent, an invention had to be new, though the definition of "new" has significantly changed since then (Biagioli 2006a, p. 1132). But perhaps the most significant difference between Galileo's context and ours is that patenting in late sixteenth-century Venice did not necessitate describing the principle or idea of one's invention in sufficient detail to enable a third party to build and use it. That requirement was introduced in different countries around 1800 (Biagioli 2006a, p. 1132). Instead of what we now call an enabling specification of the invention, in sixteenth-century Venice and in virtually every other European country at that time the inventor had to show that s/he had reduced the invention to actual practice—what Galileo called "reduction to perfection"—and that the invention performed the useful

9. "I say that it has already been ten years since, having reduced to perfection an instrument of mine which I called the Geometrical and Military Compass, I started to show it to various Gentlemen, showing them their use and giving them the Instrument and its instructions laid out in writing."

function the inventor had claimed for it. Perhaps one could say that while inventions are now legally disclosed through text and diagrams in the patent applications, in the early modern period they were conveyed through apprenticeship, by transmitting the embodied knowledge necessary to build and operate it. This distinctly "materialistic" or "pre-representational" perspective construed the invention as the specific device or working model submitted to the patent-granting authorities, not as the "idea" or "principle" of that machine or of others equivalent to it. Existing only *in re*, an invention was not yet what we call an object of intellectual or intangible property. Galileo himself conveyed his patented water pump, "viva voce, with a material model"[10] (Galilei 1890–1909, vol. X, p. 87), while the engineer Giuseppe Ceredi commented in 1567 that "anyone who believes to have found some ingenious beautiful things takes his models [to Venice] to obtain privileges" (Ceredi 1567).

Somewhat surprisingly, Galileo did not patent the compass but, had he tried to do so, he would have qualified as its inventor by virtue of having produced and sold it. Even better, the fact that he could teach the compass' operations to his students (and that the students kept signing up for his tutorials) proved that what he had was not a prototype but a fully functioning calculator on which he had built a successful business. His capacity to teach the invention proved that he possessed it to begin with. At the same time, this apparently straightforward definition of inventorship did not provide an easy way to identify precisely what the object was that Galileo was the inventor of. "I can transfer, therefore I have." Yes, but *what* did you transfer? And did you always transfer the *same* thing?

One way to address this question was to require inventors to produce and deposit a working model. But because Galileo never patented his compass, there was no official model of it and, without that, no clear record of what could count as his invention, or whether it had enough of a stable identity to be treated as an object. Until 1601 he produced, taught, and sold a series of different compasses, which he referred to as one single invention—"my compass." Under normal circumstances, it would not have mattered that he was the clear inventor of an unclear invention. As he told the *Riformatori* at the trial, had he not been warned of a lurking plagiarist, he would have liked to continue to improve the compass for a while longer, before printing a book to make that final version "very

10. "Io non mi trovo disegno buono per spiegar la fabbrica et l'applicazione della mia macchina per cavar acqua: pero' [...] con la viva voce e con un modello materiale, li potro' dare migliore satisfazione ..." Galileo to Baccio Valori (April 26, 1602), Galilei 1890–1909, vol. X, p. 87.

well-known and very widely disseminated"[11] (Galilei 1890–1909, vol. X, p. 172). The identity of his invention could have remained a moving target for a few more years, but fear of appropriation changed that. It had to be frozen.

Because Galileo primarily used it as a component of his instrument making and teaching business, "Galileo's compass" referred to whatever the instrument was that he taught and sold to the students at a given time, in the same way "Ford cars" refer to whatever cars a Ford dealership happens to be selling, irrespective of the fact that models change every year. However, concerned about a possible dispute, Galileo felt he needed to give the instrument a more distinct and stable identity so as to stake and better defend his claim to its inventorship. The objects involved in disputes over observational or experimental claims become clearly identified at the closure of those disputes, but here we see that the compass was stabilized in preparation for a dispute over its inventorship, as the result of becoming a potential object of appropriation. In this context, the *Operazioni* functioned as a "NO TRESPASS" sign that marks the property it is supposed to protect, identifying it in the process.

One of the ways in which modern patent law determines whether an inventor has the invention s/he claims to have depends on his/her ability to represent it in sufficient detail to enable a third party to replicate it. Neither Galileo nor early modern Venetian patent law, however, thought that publishing a verbal or pictorial description of an invention proved that one actually had such invention. You could use a publication to claim or advertise that you invented something, but that could not prove that the invention actually existed and that you possessed it. The description could be inaccurate or even fictional, disclosing an invention that did not work, could not work, did not exist, or could not possibly exist.[12] For instance, Galileo argued that Capra was not the inventor of the compass described in the book he had published on it because his description of its operations, riddled with errors, did not make sense.[13] They looked geometrical but they were, as he put it, "worse than hieroglyphs"—mysterious

11. In the introduction to the *Operazioni* he also mentions that, due to time constraints, he decided not to include a detailed *fabrica* section in the book (Galilei 1890–1909, vol. II, p. 370).

12. Several of these issues are discussed in Paolo Galluzzi 2020, pp. 163–211.

13. "[S]occorso mi fu dalla fortuna apparecchiato; e questo fu un grandissimo numero di nefandissimi errori sparsi per tutta quell'opera [...] la quale crasissima ignoranza stimai [...] potermi essere per saldissimo argomento, quando tutte le altre giustificazioni mi fussero mancate, a far costare la verità, col dimostrare lui impudente, e non meno stolto, usurpatore delle invenzioni mie." The same argument was repeated in the *Difesa* (at pp. 547–8, twice) and at p. 546, concerning another alleged appropriator. Also at p. 555: "quanto da questo apertamente si comprendeva come egli mai non aveva considerate, non che pratticato, questo Strumento, del quale si faceva inventore."

marks nobody could decipher at that time[14] (Galilei 1890–1909, vol. X, p. 559). Along those same lines, you could claim to have invented a perpetual motion machine, but there could be no functioning referent behind that verbal or textual claim. Finally, the mere existence of a publication could not certify that its author even understood what s/he wrote in it. One could claim inventorship of a properly functioning instrument described in a publication but could be later shown to have lifted that description verbatim from some other source without comprehending what s/he was copying.

A publication could, at best, describe an invention but could not certify that the author of that publication was the inventor of the invention it described because "having an invention" typically meant being able to show it at work and teach it to a third person.[15] A publication, however, was perfectly appropriate to secure authorship of any type of claim or work reducible to textual form: a scientific claim or observation, a poem, a music score, or the description of an instrument. One could easily be the author of a book about the compass without being the inventor of that compass. Galileo's opponent, Baldassarre Capra, largely fell in that category. While Galileo wanted to produce, teach, and sell his instrument (and thus be recognized as its inventor primarily in relation to his teaching business), Capra seemed primarily interested in receiving authorship credit for the book he wrote about the compass, with the goal of gaining visibility and securing a job as a physician, possibly a court physician. It is not clear, in fact, that Capra ever built the instrument. Their goals and strategies could have remained complimentary. Galileo could have had his compass and Capra his book.

However, for reasons whose analysis would exceed the confines of this article, each of them took extra steps that created overlaps, and thus conflict. Galileo was mostly concerned with the compass as an invention to teach and sell, writing its instruction manual for pedagogical purposes, not as a publication. Eventually, however, he turned those instructions into a book to warn off a possible copier he had heard about (who, at that point, may or may not have been Capra). Conversely, Capra may have initially

14. "Non sono molto esercitato nell'indivinare i sensi di figure non geometriche, ma peggio che ieroglifiche, poste senza costruzione, senza demostrazione, e forse senza proposizione e senza proposito, e poste più, per mio avviso, per spaventare le menti de i semplici." (Galilei 1890–1909, vol. II, p. 559).

15. Symmetrically, being able to teach an invention to others showed that that person possessed that invention (and thus was an inventor according to the early modern meaning of the term). However, unless a working model of that invention was deposited somewhere, there would have been no way to determine the identity of the invention taught by the inventor. Such was Galileo's predicament.

planned to publish a compendium book about the compass, helping himself to material published by other mathematicians, including Galileo's manuscript instructions, which was not an unlawful action according to the laws of the day. Eventually, however, Capra's book ended up including an implicit but easily recognizable accusation that Galileo, contrary to his high-decibel claims in the *Operazioni*, was not the compass' inventor. This complicated and energized Galileo's further response. He had started by fearing that somebody was going to appropriate his compass as an invention, but ended up taking Capra to court claiming, among other things, that Capra's book was injurious to his honor. Galileo was not able to produce any evidence that Capra had actually copied and sold his compass, but reframed his attack based on the publication of Capra's book, claiming that he had libeled him by implying he had lied about being the true inventor of the instrument. The ensuing dispute was as virulent as it was confusing, involving claims that continuously straddled the line between plagiarism of books and appropriation of inventions or between scholarly norms and Venetian laws.

Ironically, the *Operazioni* was the first book Galileo ever published, though he only became an author to buttress his status as an inventor. And while he relentlessly accused Capra of having plagiarized his instrument, in the end he pursued him for something resembling libel and for other book-specific injuries, like having copied the *Operazioni* into his *Usus et fabrica circini*. Finally, because Galileo had not patented the instrument, the dispute did not and could not take the legal form of patent infringement. It was litigated, instead, as a book plagiarism case in front of a specialized politico-bureaucratic body overseeing both the University of Padua and the Venetian publishing industry. Capra was condemned for having copied substantial parts of Galileo's book and translating them into Latin, and for having stained Galileo's honor and that of the university where he taught (Galilei 1890–1909, vol. X, p. 560). The compass itself was not mentioned in the sentence given that this had become a book plagiarism and libel case, and yet the instrument was clearly part and parcel of the court proceedings. In preparation for Capra's interrogation, a small desk was brought in with Capra's book and Galileo's compass on it (Galilei 1890–1909, vol. X, p. 550).

Still, at the core of this remarkably complex set of claims, moves, and slippages between books and machines the question remained: what was Galileo's compass? How could that question be settled? And how would the relationship between the compass and its instruction manual factor into that determination? Although Galileo ended up pursuing Capra not for the appropriation of his instrument but for having stained his honor (by accusing him not to be the inventor of the compass and implying he had appropriated it from somebody else), he still had to show that he was the true and legitimate inventor of his calculator, so as to prove that Capra had libeled him. The identity of the instrument was absolutely central to that determination despite the fact that property per se was not the issue. In other words, Galileo had to show that he was the inventor of the compass so as to prove that Capra had libeled him, not to argue that his property rights had been violated.

Why Not Patent?

It is worth asking why Galileo did not try to avoid all this trouble by taking out a patent on the compass instead of publishing the *Operazioni*. Much of that, I argue, had to do with the fact that the compass, being a mathematical invention, straddled the line between text and machine, between the domain of copyright law and that of patent law. We have seen the replaying of similar tensions in modern debates over the intellectual property status of software, specifically on whether it is an authorial work or "a machine made of text" (Samuelson et al. 1994, p. 2320).

Venice had granted patents for centuries, and Galileo himself sought and obtained a patent for a water pump there in 1594.[16] The novelty of his instrument should not have been an issue. It was not as unique as Galileo claimed it was—there were several instruments by Italian and European mathematicians that displayed family resemblances to Galileo's—but it easily exceeded the strictly local standards of novelty, that is, "new in Venice" rather than "new in the world" required for patents in the early seventeenth century[17] (Biagioli 2006b, pp. 147–52). While he did not explain his decision not to seek a patent for the compass, we know that he previously patented a water pump, going so far as to borrow money to have a good model produced (Renn and Valleriani 2001, pp. 481–503). What made the compass different from the water pump? Also, does it mean that there was some commonality between the compass and the telescope, given that he did not patent it either?[18]

16. On the water pump patent see Galilei 1890–1909, vol. XIX, pp. 126–9. On the protection of invention in Venice see Giulio Mandich (1948, pp. 166–224, 1960, pp. 378–82); Frank Prager (1946, pp. 109–35); Roberto Berveglieri (1995); Luca Mola (2004, 2007). On the protection of printed books see Leonardas Vytautas Gerulaitis (1976); Horatio Brown (1891).

17. Prior art would not have been a problem unless there was already an established local manufacture of that instrument in the area, which was not the case.

18. Independently from whether he did or did not actually patent a specific invention, pump, compass, telescope, Galileo always acted as an early modern inventor. This is especially exemplified by his secretive attitude and reluctance to disclose the "secret" of his inventions or instruments; a non-disclosure that early modern patent law, unlike the current one, had no problem with. He never published a book about the pump, and the books

It is possible that, given how easy it was to copy the compass, the authorities might not have bothered to grant a patent.[19] Its simple mechanical design (two flat metal legs hinged at one end) and its very visible calculating lines (much closer to a text than to the gears of a machine) made copying a compass probably easier than either producing a pirated edition of a book. For instance, when Galileo decided to present Prince Cosimo de' Medici with two silver compasses in 1606, a Medici official had a Florentine artisan prepare the blank instruments according to his specifications. The same official then had a certain Master Raphael, probably an engraver, inscribe the calculating lines on the legs using as a

he published about the compass and the telescope did not describe how to produce those instruments. In early modern terms, they were *usus*, not *usus et fabrica* books (on Galileo's non-disclosure of the telescope see Biagioli 2006c, pp. 119–29). What seemed to matter the most to Galileo when he decided whether to patent or not his inventions was the nature of the device and the business model through which he planned to extract value from it. The pump was a machine he obviously hoped to sell for others to use. The compass, instead, was an instrument her extracted value from not just by selling it but mostly by teaching it. It does not look like he ever thought about the telescope as something he would enrich himself from selling it en masse, focusing instead on the value he could extract from the discoveries he was able to make with that instrument. His view of the telescope's value, however, changed quite radically very early in 1609, after he realized the philosophical importance of the discoveries he was making. Prior to that, he had pitched his telescope to the Venetian authorities as a military instrument, seeking a reward for it. While that did not take the shape of a patent, it was not conceptually removed from the logic and protocols for the protection of inventions, especially military inventions. I have tried to show that, in fact, Galileo presentation of his telescope to the Senate in the summer of 1609 may have occurred at the same time, and in competition with, a similar presentation by a northern European inventor who was seeking a reward (probably folded together with a patent) for a competing telescope from the Venetian Senate. In sum, Galileo's showcasing of the telescope was *formally* congruent with a patent application for a military technology, where the invention cannot be sold on the market (which would defeat its military value for the Senate) but is instead "donated" to the Republic in exchange for a reward. Military inventors would typically receive pensions or positions at the Arsenal, or a mix of both, while Galileo received tenure and a much higher salary from the university. The two types rewards are materially different and involve different institutions, but they share the same logic: a gift of a technology to the Senate with the guarantee of not divulging the invention to anybody else, in exchange for a secure position and/or monetary compensation. Therefore, while it is formally correct to say that Galileo never received a patent for the telescope, the modalities he followed in his presentation were formally comparable to the protocols that a inventor would follow while pursuing a patent for a military technology in Venice (Biagioli 2010, pp. 203–30, esp. 224–9). If Galileo initially perceived the telescope as a kind of invention to be patented, that would indicate that the compass was different from both of his other inventions. Both the pump and the telescope were just machines. The compass was something else.

19. On the failed attempts to patent the earliest telescopes in the Netherlands see Van Helden (1977).

template another compass Galileo had left in Florence with that same Medici official the previous summer, "so that, with that example, he will be unable to make any mistake" (Galilei 1890–1909, vol. X, p. 157).

That one could make virtually identical copies of compasses is both important and anomalous because, in the early modern period, copying machines was much more likely to yield imitations than identical replications. Galileo's telescopes, despite being rather simple devices, were never even close to identical, due to the hand-grinding of the lenses.[20] Exact copies of complex machines had to wait till about 1800 with the introduction of interchangeable parts manufacturing.[21] But if you had access to one of Galileo's compasses and knew a skilled artisan, you could have a virtually identical replica made of it. Its "textual" form made it easily reproducible. Copying a compass was a lot closer to making a measuring rod than to reproducing a windmill.

Furthermore, while copying a complex machine would have required an understanding of that machine, the Medici official could rely on an artisan who, while skilled at engraving or fine metalwork, could copy the compass without needing to understand what it did, or how to use it.[22] He just measured and transferred the lines and their divisions from one leg onto another. The compass, in sum, could be copied almost the way music or film is pirated today, by people who can press a button but do not need to know anything about music or film. None of the tacit knowledge that may have been required to copy a TEA laser or Boyle's air pump was involved in copying Galileo's calculating instrument (Collins 2010; Shapin and Schaffer [1985] 2017). This had much to do with the fact that unlike Pascal's, Leibniz's, or Babbage's calculators, Galileo's compass calculated through lines, not complex gears; lines could be replicated as easily as words in a book (Jones 2016).

Between Brass and Paper

The compass was not a unitary instrument like a telescope or an air pump, but a material platform for several different sets of lines, each defined by its

20. Arguments about the impossibility to produce identical copies of machines (as opposed to the possibility of producing identical editions of books) were commonly deployed to differentiate between patent law and copyright law, and to argue that inventions could only receive weaker protection than printed books because of that. On this wide-ranging debate, see Burrow (1773, p. 56).

21. The exception were devices like cannons that could be produced by casting, and then bored to the appropriate caliber. While we could say that they were "mass produced," these were very simple machines with no moveable parts.

22. This was obviously *not* the case with early calculating machines through complex gears rather than lines, see Jones (2016).

specific division, which could be inscribed on either the recto or verso face of the compass' flat legs. The specific choice of lines varied from instrument-maker to instrument-maker though some, like those to perform simple arithmetical calculations, tended to be present in most exemplars. In one case, the instrument-maker, Michiel Coignet, included so many lines that he literally ran out of space. His answer was to distribute the lines over two instruments; a choice that raises the question of whether Coignet's instrument was one or two or whether, instead, we should identify the compass not with its hinged flat legs but with its formal features—the lines—treating each set as a distinct instrument, or as a distinct "software app" running on a "general" brass computer[23] (Hulpeau 1626).

As these calculators circulated, mathematicians added new lines of their own invention and dropped old ones. In his 1612 Latin translation of Galileo's *Operazioni*, Bernegger added two sets of lines, while commenting on how many more the instrument could accommodate. In 1610, Johann Faulhaber published a book on an instrument nearly identical to Galileo's, which was in fact based on Faulhaber's study of an instrument that he later learned to be one of Galileo's. Even in this case, Faulhaber picked and chose some lines of Galileo's while adding more of his own (Drake 1978). The same kind of bricolage of new and old sets of lines is found in the compass brought to Padua around 1602–3 by Jan Zugmesser, a German mathematician who joined the household of the Archbishop of Cologne and a few years later, in 1610, became a critic of Galileo's telescopic discoveries. Zugmesser's compass contained some of the lines of Galileo's instruments, as well as different ones[24] (Galilei 1890–1909, vol. X, pp. 366, 370, 417, 492). Around the same time, Clavius, the chief mathematician of the Society of Jesus, published his *Geometria practica* where he illustrated a flat-legged brass calculating compass. Together with a copy of the book, Clavius sent Galileo a letter in December 1604 asking for one of his compasses because "although in my *Geometria practica* I have included a similar instrument shown to me by a certain German, I like yours much better because of the variety of its uses" (Galilei 1890–1909, vol. X, p. 121). While appreciating its specific qualities and

23. If we define an instrument in terms of its material parts, then we could say that Coignet's was either two instruments or one instrument in two parts (like a book with two chapters). But if we define the instrument in terms of its function, then there would be as many instruments as lines, no matter the number of material platforms those lines are spread over.

24. See also the discrepancies in the different reports of this event: Cornaro in *Difesa*; Hasdale in Galilei 1890–1909, vol. X, p. 370; Heilbron 2010.

versatility, Clavius perceived Galileo's compass as a member of a known class of instruments.[25]

In the case of the telescope, copiers needed to reverse engineer its optical scheme and learn how to grind lenses that were significantly different from those produced by spectacle-makers (Helden 1977, pp. 1–67). By contrast, copying the compass was more like copying a text from an easily accessible original. The lines were right there, engraved on the brass legs for everybody to see (Figs. 1 and 2). While laying down the lines and their division was a precision job, artisans were able to simply copy the divisions off another compass, as the Medici engraver did in 1606. Furthermore, the lines could have been copied even by taking a tracing of the instrument, that is, by using the instrument as a plate to print itself. That printout alone would not have produced a workable paper compass; the image would have been reversed, but it would have contained all the information needed to produce a functionally identical brass instrument (Jardine 2016, pp. 36–42). A tracing could have been an interesting option if one had access to a compass only briefly, without enough time to measure the spacing of the marks on the lines.

Text-like features of the compass can be also found in its mobility and evolution, which may be compared to the circulation, commentary, editing, abridging, of books and manuscripts. Each compass might be seen as an anthology of new and old lines of calculation—an edited instrument, so to speak.[26] The ease with which the compass could be edited, abridged and expanded into a different instrument had the symmetrical effect of making it difficult to trace what the original edition was, and the identity of its author. Tracing the compass' prior art would have been a philological, rather than engineering challenge. Stillman Drake has proposed to identify Galileo's compasses by checking if they "have exactly the scales …, in the same order of arrangement and with the same abbreviations and

25. As confirmed by the fact that Clavius did not even mention the name of the German artisan in his book, thus treating the compass and its maker as effectively generic (Clavius 1604, pp. 4–5).

26. This does not mean that the notion of priority could not apply to these instruments and that Galileo's authorship claims were groundless. Rather, we are dealing with a complicated scenario of composite authorship, one where each contribution, each set of lines, is individual and distinct and, as such, can be potentially traced to its author; a bit like the infringement of a free software license can be easily assessed by comparing the disputed sequence of instructions with that of the original archived code. In theory the "intellectual property" aspects of a calculating compass like Galileo's are much easier to assess than whether or not the script of a Hollywood movie has plagiarized Jane Doe's novel (or whether, say, Divini plagiarized Torricelli's telescope lenses). At the same time, while the forensics would be simpler, at least in principle, what is hardly manageable is the actual research work necessary to reconstruct the genealogy of a specific compass.

markings"—an approach that seems closer to that of philologists than historians of technology (Drake 1978, p. 31). In sum, the compass was a strange kind of machine that resembled a text or a print in ways that would have made patenting both difficult and toothless. And, unfortunately for Galileo, the compass could not be protected as a text either because printing privileges did not cover machines; unless they were printed paper instruments, which the compass could have easily been.[27]

Joined at the Hip

There is another less obvious textual dimension to the compass that greatly impacted the way it could be claimed and replicated as an invention: its symbiosis with its instructions. The *Operazioni* had such a tight relationship with the compass that Galileo warned that the instructions book would be "completely useless to those who receive it without the instrument"[28] (Galilei 1890–1909, vol. X, p. 370). And even those who already possessed the instrument would have difficulties understanding the text unless they had previously listened to Galileo's instructions and observed his hands-on demonstrations. (Galilei 1890–1909, vol. X, p. 370). He reiterated the same point at the trial:

> Have I not written [in the *Operazioni*], and have I not said viva voce a thousand times that the book without the Instrument is worth nothing? And that even with the Instrument but without direct instruction and without seeing its uses demonstrated in practice, it is tedious and difficult and unable to deliver [the compass'] most attractive features? (Galilei 1890–1909, vol. X, p. 370).

The symbiotic relation between instructions and instrument was even stronger when the instructions existed only in manuscript form, which was for about nine of the ten years during which Galileo produced and sold the compass prior to the dispute with Capra. In that period, he often referred to the compass and the instructions in the same sentence, which is consistent with what we find in his accounting records, indicating that they were sold together (Galilei 1890–1909, vol. X, p. 586). Similarly, the affidavits from Galileo's students that were produced at trial consistently reported having received from him both the instrument and the instructions. We find the same in Galileo's correspondence, where friends who

27. Turner 1989, pp. 23–42; Gingerich 1971, 1993; Bryden 1997; Bennett 2003, pp. 140–1; Eagleton and Jardine 2005; Karr-Schmidt and Nichols 2011; Jardine 2016; Karr-Schmidt 2017.

28. "[R]endera' questo trattato del tutto inutile a chi senza lo Strumento ei pervenisse nelle mani."

asked him for a compass also asked, in the same line, for the instructions. Galileo himself followed that practice when sending his instruments as gifts (Galilei 1890–1909, vol. XIX, pp. 150, 151, 154). Finally, there are two instances in which the compass and the instructions are referred to as the same thing, or perhaps two embodiments of the same object. Writing to Galileo from Florence in 1604, a court official reported that the Medici welcomed Galileo's decision to dedicate "said instrument and its instructions" to Prince Cosimo, conveying the sense that this was one gift in two complementary parts—machine and text[29] (Galilei 1890–1909, vol. X, p. 144). Then, as we have seen, Galileo referred to his compass as something that he both made and printed: "I have given [the compass] to many gentlemen of various countries, always presenting myself as its author and inventor. As a thing of mine, I had more than one hundred built in Padua and other cities. As a thing of mine, I have recently printed it"[30] (Galilei 1890–1909, vol. II, p. 543).

No matter whether we take Galileo's claim literally or metaphorically, it is clear that the *Operazioni* was not, by his own admission, a free-standing book about the compass that a reader could understand without help. Printing only sixty copies (which he distributed himself, from home) indicates that he did not intend to deliver the slim book to a general audience, but simply meant "to give it out with the instrument" as a memory aid for its users (Galilei 1890–1909, vol. X, p. 370). Given that the book described only the use of the compass, not its construction, it could be relevant only to readers who had the compass already. Conversely, it would have been useless to those who only wanted to learn more generally about the instrument. The instructions could only function with that instrument, and the instrument with those instructions[31] (Galilei 1890–1909, vol. II, p. 370). As a hyperbole-prone but perceptive admirer put it: "with the [*Operazioni*] you have given a soul to the compass"[32] (Galilei 1890–1909, vol. X, p. 256). Without the instructions, the compass was lifeless, unable to perform its functions. Like a computer without software.

29. Vincenzo Giugni to Galileo, June 4, 1604: "[…] la volontà di V. S. esser d'indirizzare detto strumento et ragion d'esso all'Altezza del Principe nostro."

30. "[I]o l'ho conferito da dieci anni in qua a moltissimi Signori di diverse nazioni, chiamandomene sempre con tutti autore et inventore; io, come cosa mia, ne ho fatti fabbricare più di cento in Padova ed in altre città; io finalmente come cosa mia l'ho stampato."

31. "Aggiugnesi che il tacere io la fabrica dello Strumento […] renderà questo trattato del tutto inutile a chi senza lo Strumento ei pervenisse nelle mani. E per tal causa ne ho io fatte stampare appresso di me 60 copie sole, per presentarne insieme con lo Strumento."

32. Andrea Morosini to Galileo, September 4, 1609, "Con quello dell'uso ha dato l'anima al compasso".

Virtually identical to the 1601 manuscript version of the instructions, the *Operazioni* were old wine in a new bottle that Galileo produced in response to two contingencies.[33] The first was the need to secure a public notice of his priority to try to block possible appropriators (Galilei 1890–1909, vol. X, p. 172). The second had to do with the fact that, for most of its life, Galileo's compass had not been a stable object.[34] Because the *Operazioni* did not describe the instrument itself but only its uses, the book could not function as a proper "no trespassing" sign as it was not clear where exactly the claimed property started or ended. Also, it could not function as a priority registration either, given that it did not properly disclose the instrument—a public disclosure that, according to Galileo, he had already delivered through teaching it to students.

Galileo's invocation of the "testimony of print" therefore referred to something more specific and technical. It was a function the *Operazioni* performed not primarily through its content but through the traces of its publication. That is, it did not just function as a text but as an object—a bureaucratic object constituted by administrative practices such as its licensing and its registration with the Venetian printers' guild. Galileo

33. Because of space constraints, I can only mention two more: Securing a longer-term university contract, and producing a suitable gift for Prince Cosimo de' Medici. Concerning the first, Galileo's last four-year contract expired in September 1604 and he had been teaching on a year-to-year basis since (Galilei 1890–1909, vol. XIX, p. 114). He had been pushing for both the renewal of his university contract and a substantial raise (Galilei 1890–1909, vol. X, pp. 105, 147, 149–50, 157–9). The *Operazioni* seemed to help his case. When the new contract came on August 1606 it mentioned the forthcoming book as one of the reasons for his reconfirmation and a hefty 50% salary increase (Galilei 1890–1909, vol. XIX, p. 114). Galileo had received the license for his book only six weeks before, on June 26. Concerning the second, by dedicating the *Operazioni* to young Prince Cosimo, Galileo was trying to lay the groundwork for his move to the Medici court which he eventually obtained in 1610. Since 1601, Florentine courtiers had been pressing him to dedicate the compass to prince Cosimo to strengthen his relationship with the future grand duke (Galilei 1890–1909, vol. X, p. 84). It took Galileo about five years to follow up on the suggestion, making it a somewhat stale gift (the compass being ten years old by then), but it all seemed to work out in the end (Wilding, *Galileo's Idol*, p. 44). Right after Galileo expressed his desire to dedicate the book to Cosimo in June 1605, the grand duchess Christina invited Galileo to come to court that summer to teach mathematics, including the sector, to the prince (Galilei 1890–1909, vol. X, pp. 144, 149).

34. "This is one of those subjects that do not allow themselves to be described or understood with clarity and ease unless they are first heard viva voce or observed while practiced. And this would have been a powerful reason to prevent me from print this work had I not heard that somebody [...] was getting ready to appropriate it. This put me in need to secure, with the testimony of print, both my works and the reputation of he who might appropriate them," Galilei 1890–1909, vol. II, p. 370. He repeated this claim—"to block the road to those who wanted to steal my labors"—in his April 9, 1607 denunciation of Capra to the Riformatori (Galilei 1890–1909, vol. X, p. 172).

was not claiming his invention by making it public in the *Operazioni*, but rather producing a timestamp through the book for his claim that he had an invention which, following the customary practice of inventors, he was not fully disclosing. (In this sense, the *Operazioni* functioned a bit like a cipher or like the *plis cachetés* that scientists used to deposit by the thousands with the Secretary of the Paris Academy of Science to secure a timestamp for the claim that they had a claim they were not disclosing) (Berthon 1986, pp. 71–8). Filling in what the claim was was done by the students.

From Memory, With Text

The way the *Operazioni* did ultimately provide effective evidence of Galileo's inventorship of the instrument it did not disclose becomes clearer when we read the affidavits that his students submitted at the trial. Giovanfrancesco Sagredo, the Venetian patrician later immortalized in Galileo's *Dialogue*, wrote:

> I faithfully state […] that already about nine or ten years ago I received from […] Galileo Galilei […] one of his instruments which he calls the Geometrical and Military Compass, and a similar one, shortly after, with some lines slightly modified, and others extended to handle larger numbers. *And this instrument is exactly the same as that whose use he printed a year ago* under this title: *The Operations of the Military and Geometrical Compass*, and whose instructions I received in writing and voice together with the instrument at the aforementioned time […][35] (Galilei 1890–1909, vol. II, p. 534).

Jacques Badover (who would later play a role in Galileo's development of the telescope) confirmed that:

> I […] declare and testify as the truth that […] not only did I see various of his Geometrical and Military Compasses, but I received one of them, and also its instructions. I was also shown [by Galileo] the rules he followed to build it and mark its divisions, which at that time he was busy with. And he modified and improved them compared to those he had placed in the other Compasses he had previously caused to be produced. And, furthermore, I saw […] how

35. "Faccio fede […] aver gia' […] dieci anni in circa havuto dall'Eccellentissimo Sig. Galileo Galilei Lettor di Matematiche in Padova, uno de' suoi strumenti chiamato da lui, Compasso Geometrico, & Militare, & un'altro simile, poco dopo con alcune divisioni un poco mutate, & con altre estese a maggiori numeri, il quale strumento e' quello stesso a' punto, del quale l'anno passato ne stampo' l'uso sotto questo titolo: Le Operazioni del Compasso […], la qual dichiarazione hebbi in scrittura, & in voce insieme allo strumento al sopraddetto tempo […]"

> many of these same instruments were by their aforesaid Author communicated to various Gentlemen of different nationalities.
> And that instrument is the same as the one whose operations have been printed last year by the Author here in Padua with the title *Operations of the Geometric and Military Compass of Galileo Galilei*...[36] (Galilei 1890–1909, vol. II, pp. 534–5).

Both Sagredo and Badover explicitly acknowledged the mutations the compass underwent over the years, but then crucially invoked Galileo's 1606 book as providing a snapshot of the instrument's latest and permanent incarnation, which they were familiar with. That seemed to create a stable version of reference for the object Galileo claimed to have been appropriated by Capra.

But the evidence of the compass' stability and identity provided by Sagredo and Badover is essentially different from what one could have derived from a patent model. It did not result from matching a device one has seen with the one instantiated by the archived replica. Notice that neither student stated that they simply and directly identified the instrument they were taught by Galileo with the one described in the *Operazioni*. Both carefully stated, instead, that the book contained the *uses* of such instrument: "this instrument is exactly the same as that *whose use he printed*" and, "that instrument is the same as the one *whose operations have been printed* last year," thus confirming that the instrument itself was not described in the book. So how could the *Operazioni* be said to establish the identity of an instrument it did not describe? And how could the testimony of his students provide evidence that Galileo was the inventor of the instrument he claimed to have been appropriated by Capra (and that Capra instead implied that Galileo had copied from somebody else)?

The answer is right there in the affidavits. The *Operazioni* did not describe the instrument, but Sagredo and Badover could testify that the book still indexed the instrument it did not describe because they were able to recognize the instructions listed in the *Operazioni* as those they themselves had learned to perform on the compass Galileo had given

36. "Io Giacomo Badovere Francese espongo et attesto come è la verità, che [...] non pure viddi diversi de' suoi Compassi Geometrici et Militari, ma ne fui gratificato di uno, et di più della sua dichiarazione, mostrandomi in oltre le regole che teneva intorno al modo del comporlo et segnare le sue divisioni, intorno alle quali in quel tempo era occupato, et ne mutò et migliorò alcune da quello che ne gli altri suoi Compassi, prima fatti fabricare sino a quel tempo, haveva posto. E più, viddi [...] come molti de i medesimi strumenti furono dal sopradetto suo Autore communicati a diversi Gentil'huomini di diverse nazioni: il quale strumento *è il medesimo che questo, le cui operazioni sono state l'anno passato dall'Autore stampate* qui in Padova sotto il titolo di *Le operazioni del compasso geometrico et militare di Galileo Galilei* ..."

and taught them in person.[37] His former students did not identify the instrument by virtue of having seen it and subsequently being able to match its look with a static image or model of record. More than on their eyes, the identification relied on the mental and muscle memory of how they had moved the instrument to perform various calculations, after Galileo had taught them how, and how that memory matched the instructions printed in the book. In other words, Sagredo and Badover did not identify the instrument (the way an ornithologist may match a photo of a bird with an image of reference), but they rather re-cognized it not as an object they had seen already but one they had used before. Notice that, unlike matching, recognition requires a movement back in time, not to recall an object but a movement. In this sense it is not a "replication" of an event in the present (like, say, an experiment) but the precise recollection of a knowledge-producing action in the past—an action that could only involve a user.

The *Operazioni* played a crucial role in this process of identification, but not as textual descriptions of the instruments, which they were not. It functioned as a memory device or "time machine" that returned Sagredo and Badover to Galileo's house, a few years back. The book did not mirror the compass but the students' memory of what they had done, there and then. (At the trial, Galileo claimed that Capra could have not possibly understood the compass given that he did not even know how to hold it in his hands)[38] (Galilei 1890–1909, vol. II, p. 584). Thanks to the memory of their experience learning and using the compass, Sagredo and Badover were able to align all the various evidential elements that, held together, constitute a distinctive object: (1) Galileo had that invention because he had taught and transferred several versions of it to them; (2) that invention had eventually developed a stable identity; and (3) such identity was indexed (but not described) by the *Operazioni*.

At a time when invention was defined not by what it was but by what it did, it should not be surprising that the identity of an invention would not depend on the static match between two representations—a machine on one hand and its description of record on the other—but on a match between the embodied memory of the users and the text of its instructions. The identifying match was not between two objects but between two

37. That they were able to identify the instrument through its instructions, without its description, confirms how symbiotic the relationship between instrument and instructions was. It also makes Galileo's friend's aforementioned statement that the *Operazioni* were the "soul of the compass" sound less hyperbolic.

38. Also related: "Costui non è un sonator di liuto, che erri nell'aria, nella battuta, nel contrappunto; erra nel tener lo strumento in mano, appoggiandosi le corde al petto, ed applicando la man destra alla tastiera" (Galilei 1890–1909, vol. II, p. 587).

doings, one embodied and one described textually in the instruction manual.

Instructions as Models?

Having repeatedly differentiated the role of the *Operazioni* from that of a model, it may seem strange to conclude by trying to analogize them. But there is a specific sense in which the instructions could be seen as functionally equivalent to a working model, that is, not a model resting on a shelf, but one that displays how the invention works in time, as it performs its function (Pottage 2011, pp. 621–43). Instructions are textual and working models are material, suggesting an essential qualitative difference between the two. But in fact both instructions and working models, when inserted back into the pedagogical practices of which they were integral part, share a crucial feature: they show and/or simulate time, enabling an understanding of the invention in motion, either continuous motion (as in a windmill) or step-by-step motion (as in Galileo's compass). It is that pattern of motion that identified it—a movement that lawyers construe as the principle or idea of the invention, and mathematicians regard as the steps constituting a calculation (Pottage 2011, p. 625).

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