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INSTRUMENTS ADRIFT: 17TH CENTURY VICISSITUDES OF THE HARMONIC WORLD

lecture, kindly delivered *in loco authoris* by Penelope Gouk, for a conference held 23/24 January 2004 in Bologna on
'The organon of music. The musical instrument as a scientific instrument'

- *Alvus tumescit virginis* (played on a church organ built c. 1710 in Westphalia; now in Utrecht, Netherlands)
- Praetorius and Mersenne: Similarities and significant contrast
- The harmonic world intact, disturbed, and repaired
- The harmonic world unravels after all
  - ⇒ instrumental gnawing at the edges (Vincenzo Galilei *et al.*)
  - ⇒ crisis widened due to new modes of thought about the natural world:
    1. mathematical-experimental (Galileo *et al.*: consonances as coincident vibrations; division of the octave)
    2. natural-philosophical (Beeckman, Descartes: instruments inside the listener's head)
    3. fact-finding experimental (Bacon *et al.*: instruments as acoustic source)
- In conclusion:
  - ⇒ a new role for number
  - ⇒ theoretical vs. practicable solutions to practical problems: a chasm bridged when?
  - ⇒ thanks, and good wishes

I greatly regret my personal absence from this conference with its interesting, truly interdisciplinary subject.
I have prepared this lecture using two books of mine:
Quantifying Music. The Science of Music at the First Stage of the Scientific Revolution, 1580-1650 (Dordrecht: Reidel,1984),
and one nearly completed under the provisional title of
'How Modern Science Came Into the World. Six Revolutionary Transformations And The Dynamics Behind Them'.
I wish you all a very productive and stimulating meeting.

The piece you have just been listening to is 'Alvus tumescit virginis' by Michael Praetorius. Praetorius is the composer of ten printed and well-edited yet rarely performed organ pieces, and of a vast range of no less expressive choral works. But of course he is also the author of *Syntagma musicum*; that densely packed, detailed source of near-exhaustive information on the state of music by the early 17th century. What, over and beyond that, makes the *Syntagma* special is that in surveying the contemporary scene it documents the outcome of one of the most revolutionary developments ever undergone by music in the European tradition — the emancipation of the musical instrument. Whether or not the voices in masses or motets or madrigals in the strictly polyphonic style of the Renaissance were often or only rarely doubled by instruments, certainly their independent role in music making prior to the late 16th century was both limited and by and large subsidiary. This goes even for the queen of instruments, the earthly embodiment of cosmic harmony, of which here in Bologna you have two very early specimens at both sides of the choir of San Petronio Cathedral. I would have loved to play them if indeed bodily present here, which to my regret I am not, due to circumstances for which I beg your indulgence. I also beg your indulgence for Penelope Gouk, who is kind enough to read my text but must be absolved right away from any blame for anything you, or indeed she herself, may find wrong with it.

Not even the organ, then, or its step-sister, the harpsichord, did until late in the 16th century begin to acquire much of a role for itself independent of the human voice. The ongoing emancipation of keyboard and other instruments finds itself both expressed and embodied in Praetorius' *Syntagma* of 1615–20. Praetorius was very much a musicians' musician, that is, he addressed fellow-musicians primarily, with a view to sharing with them in all its intricacy the meanwhile vast world of instrumental music of his time, of which he sensed the relative novelty. As such, the *Syntagma* stands in revealing contrast to an in many respects similar book of encyclopaedic proportions to appear independently no more than a decade and a half later, Marin Mersenne's *Harmonie universelle* of 1636/7. That contrast between Praetorius and Mersenne seems well-suited to help introduce the theme of the present conference. Let me first illustrate it by means of an example. Compelling the advanced violin player who is speaking this text to switch momentarily to the church organ, I contrast the approach taken by Praetorius in his 2nd volume, 'De organographia', to Mersenne's in the 'Livre des Orgues', which is book 6 of the 'Livre des instrumens' which in its turn is the one portion of *Harmonie universelle* that music historians still regularly consult. In this treatise on the church organ — rightly reported by Mersenne to be found by many "the most excellent and the most perfect of all instruments, because of the great variety of its stops as well as the constancy and the purity of its sounds" — Mersenne not only recorded albeit in less exhaustive fashion many features of the organ one finds listed in *Syntagma musicum*, too, but consistently focused in addition on properties for which Praetorius had little if any use. For instance, Mersenne carefully noted the proportions between the length and the width given by organ makers to pipes of various kinds. He also took pains to establish experimentally the mistake of those who believed that irrespective of whether one halves a pipe's length or its width, the higher octave is yielded thereby. He further wondered how an increase in wind pressure affects pitch. For the last-mentioned case he characteristically wrote: "Or les Facteurs peuvent ayder à la Philosophie, en dressant le catalogue des tuyaux qui montent seulement d'un demy-ton, ou d'une Tierce, d'une quarte, d'une quinte, &c., car il sera plus aysé d'en trouver la raison, lorsque l'on cognoistra les qualitez des tuyaux qui sont cause de la difference de ces sons." [that is, "Here the makers may help philosophy by dressing up a list of pipes that rise only by a semitone, or a third, a fourth, a fifth, etc., for it will be easier to find the reason for that when one knows the properties of the pipes that are the cause of the difference between the notes."] By such passages, as also by just about the entire content of *Harmonie universelle*, as also by his not being a musician, let alone a professional one, but rather a 'philosopher' given to seeking a partly novel understanding of the natural world, Mersenne kept marking on page after page that he was directing music to in good part other ends than Praetorius had in mind. By and large, the difference in objective between Mersenne and Praetorius is none but the very difference to be addressed in course of the proceedings of today and tomorrow — music not primarily considered as sound effects produced with technical adequacy to evoke depth of devotional and other feeling, but music considered primarily as both reflection of, and pointer toward, fundamental properties of the natural world. To this primary, nature-directed objective of Mersenne there was both an ancient and a modern, not to say revolutionary, side. The ancient aspect is, of course, the Pythagorean conception of music as expressing the harmony of the world — an idea that for Praetorius as for every learned musician of his time served as self-evident background knowledge indeed, yet hardly as a matter of pressing concern. The modern aspect is the no more than partly deliberate, thoroughgoing unraveling of this very idea, to which Mersenne contributed as many in his age did, in hopes of either restoring it in a novel way (as with Mersenne or with Kepler) or (as with Galileo, or Beeckman, or Descartes, or Bacon) replacing it with something previously unheard-of, to wit, a coherent, naturalistic account of the phenomena of musical sound to be attained at least in part by means of musical instruments newly considered and handled as instruments of natural inquiry.

To be sure, such an instrument had existed for a long time; it is, of course, the very monochord that had given rise to the idea of world harmony in the first place. One might with some justice call the monochord the first scientific instrument. On its sole basis a world-view of striking beauty and intricacy had been erected, with the consonance-producing capacities of the Pythagorean *tetraktys* (integers 1, 2, 3, 4) at its center. Cosmic harmony was a grandiose way to make sense of the world by binding macrocosm and microcosm, the heavens and human beings, together through a fixed rule of numbers not selected at will but found to stand expressed in our intimate, musical experience. Cosmic harmony was a beautiful conception; it was a reassuring conception; it was also a retrospectively risky conception. Grandiose views of the world at large, such as proliferated in ancient Athens, cannot be proven (as the skeptics were quick to point out); but, as a rule, they cannot be refuted either. When, in exceptional contrast, you build a worldview upon numbers you may deservedly feel satisfied to have built on more solid ground for as long as the numbers fit well, but no sooner does the fit appear to be less than watertight or the very ground on which the conception was built is bound to turn dangerously shaky.

Over the full period of Greek philosophy, from Pythagoras to Boethius, cosmic harmony stood on solid ground indeed. True, one might with Aristoxenos reject the number game as irrelevant to the most basic feature of music making, which is not harmony but melody, and Ptolemy still took the challenge sufficiently seriously to attempt a reconciliation between the autonomy of the melody advocated by Aristoxenos and the numeric logic of the musical consonances Ptolemy, a mathematical scientist in the Alexandrian tradition, found it impossible to ignore or sweep under the carpet. No frontal attack from outside the very conception of harmony, but only the appearance of lack of fit at its inside is what could call its extension to the cosmos into serious question.

When by Carolingian times European civilization began to come into its own, it developed new modes of music making (notably Gregorian chant) and numerous practical gadgets (such as Guidonian solmization) while adopting without any significant change the heritage of cosmic harmony codified by Boethius — the sheer logic of harmonious numbers played itself out as before. Indeed, the venerable conception of cosmic harmony might have been maintained forever but for the successive intervention of three by and large independent, each uniquely European developments, to wit, the invention of polyphony, the emancipation of the musical instrument, and the rise of modern science. Briefly said, the challenge posed by polyphonic music making and by the usage of consonant, hence, non-Pythagorean thirds and sixths that by the early 14th century began to follow in its wake was, by mid-16th century, met brilliantly, in the hands of the music theorists Zarlino and Salinas. But their new harmonic synthesis came under renewed attack almost at once, due at first to questions raised by the tuning of musical instruments and soon thereafter to such new ways of dealing with numbers, with instruments, and with empirical evidence generally, as mark the event known among historians of science as the Scientific Revolution of the 17th century. For present purposes I leave aside the first crisis cosmic harmony went through, since it did not involve instruments and also was in the end overcome. I focus instead on the second crisis. Its onset was in good part due to the musical instrument in its ordinary, music-making capacity, the one Praetorius had exclusively in mind. But early on in the 17th century the crisis was exacerbated to the point of disrupting for good the conception of cosmic harmony, as one consequence of the musical instrument suddenly and unpredictably being turned into an instrument of scientific inquiry, as exemplified in Mersenne's work.

For the fully Italian onset of this second, graver crisis, I just remind you of its two strands — the bitter polemics fought out under Aristoxenos' posthumous auspices over tuning issues between Artusi, Bottrigari, Ottusi, Patrizzi and others in the 1590s, and the experiments with strings of various materials, lengths, and tensions by means of which one early participant, Vincenzo Galilei, sought in the end to clinch his no less bitter objections to his one-time master Zarlino. The retrospectively decisive turning point in this feud came when Vincenzo ceased arguing about the empirically undecidable purity of consonances actually sung, and shifted the terrain to properties of the musical instrument, which he rightly saw to provide more conclusive evidence of the purity or impurity of musical consonances as produced in actual music making. The upshot of the dual onslaught was, not to be sure the dethroning of the consonant ratios followed forthwith by the demise of cosmic harmony, but, at least with advanced mathematical thinkers of the next generation, awareness of a need to rethink and, if possible, redefine cosmic harmony all over again. In work of the late 1620s, by Kepler in *Harmonice Mundi*, by young Descartes in 'Compendium Musicae', and by Stevin in 'Vande spiegheling der singconst' ('On the theory of music'), such a reform was achieved in three mutually quite different veins, each of which was as idiosyncratic as it happened to remain inconsequential for the debate that was to emerge within a decade and took from the start another, physical guise entirely. Central to that debate, then, was the musical instrument in a new, thus far unheard-of capacity — as the source and origin of vibrations in regular succession.

Unlike in my *Quantifying Music*, in my almost completed book on how modern science came into the world I argue that the onset of the Scientific Revolution is to be regarded as the near-simultaneous, revolutionary transformation of three long-standing modes of nature knowledge:

(1) from abstract-mathematical science in the Alexandrian tradition to realist-mathematical or even mathematical-experimental science pioneered by Kepler and by Galileo;

(2) from natural philosophy in four Athenian modes to a mode of natural philosophy, pioneered by Beeckman and Descartes, in which, unlike in ancient atomism, not the corpuscles that make up the world stand at the center of attention but rather presumed regularities of their motions;

(3) from an empirical approach to phenomena centered on descriptive accuracy and practical utility, to its condensation in fact-finding experiment, as pioneered by Gilbert, van Helmont, and Harvey, and as advocated by Bacon.

That these three revolutionary transformations took place at all is a fact of history to which developments in musical theory and/or practice, even if taken in a wide sense, contributed but little; music in that same wide sense was, however, deeply affected by them. I shall now successively survey in inevitably very broad brushwork their impact on a variety of musical issues, with a focus on the part musical instruments came to fulfill therein.

The fundamental contribution from Galileo onward to come from mathematical-experimental science was to put the long-standing account of consonance due to ratios of the first few integers upon a new, physical foundation. He recognized that pitch is uniquely determined by the frequency with which a vibrating string moves to and fro. He further adopted a pulse account of sound production according to which musical sound is yielded by the successive pulses transmitted from the vibrating string through the air to the sense of hearing. This implies that, if two different notes are made heard simultaneously, pulses coincide in those cases when the intervals in question happen to be given by ratios of the first few simple integers. In the case of the octave (2:1), every second pulse yields such a coincidence; with the fifth (3:2), every sixth one, and so on, up to and including the minor sixth (8:5). As a result, the traditional range of consonance-yielding ratios is reinstated, but now linked solidly to the physical parameter of vibrational frequency. At first sight, then, the foundation-stone of cosmic harmony has been vindicated. But only at first sight. For the trouble with this account is that the fit with phenomena is actually far from watertight. For example, how is it that the minor sixth, with pulses coinciding every 40th time, is still a consonance, but not the dissonant second (9:8) or such harshly dissonant intervals as were customarily associated with the ratios 7:4, 7:5, and 7:6?

To the extent that solutions to such difficulties were sought at all (Galileo blissfully ignored them), these were inevitably of an *ad hoc* nature, designed above all to save an account for which no ready alternative in conformity with current modes of thought presented itself. It is, however, characteristic of the realist transformation which the mathematical subject of musical consonance had meanwhile undergone that solutions were no longer sought in any deep meaning of constituent numbers, but rather in certain real-world phenomena of sound, some of them freshly discovered. For example, to explain the defective consonance of the fourth Mersenne invoked the very upper partial tones he himself discovered (distinguishing, above 1 as the fundamental, harmonics 2 through 5). Or take Huygens, who invoked the 6th and 7th harmonics as well for shoring up his growing conviction that intervals with the number 7 in their ratios are pleasingly harmonious after all. So far these remained side issues; not until the 18th century was a further knowledge of upper partials and other sounding properties of vibrational motion to be turned into the cornerstone of a mostly new, once again mathematical account of consonance, destined to be replaced in its turn by one by Helmholtz (1863) in which the *perception* of musical sound got its full due for the first time.

Up to now we have seen how a fundamental reorientation in mathematical science, from highly abstract to much more realist, carried with it a novel view of musical consonance. But right from the start Galileo sought to adorn his conceptual revolution with an emphasis on practical utility, e.g., by using observation of the moons of Jupiter discovered by him for solving the problem of geographical longitude. And that is how newly realist mathematical scientists began to meddle with a musical problem that, in view of the mathematical aspects involved, they felt they might solve much better than the practitioners, themselves. After all, the dispute between Vincenzo Galilei and Zarlino had started from the mutual incompatibility of the consonances. Notably, a tonal scale with pure thirds and fifths can be, and actually was, calculated to be inherently unstable. What scale singers adopt in practice had been the very subject of their (in this respect, unresolved) dispute. Singers sing as they go along but keyboard players must tune their organs or harpsichords beforehand, so the same problem of what practicable scale to employ arises here in a more pressing manner. Pythagorean intonation was out, in view of its intolerably false thirds and sixths, as was just intonation for the reason just mentioned; adding one or more keys per octave (as the keys split between G$^{\#}$ and A^{b} here in the San Petronio) proved predictably unwieldy; the solution was most often sought in *temperament*, that is, a slight mistuning of selected intervals such as our hearing appears to some variable extent ready to put up with. By far the most common variety was 'mean tone temperament', with eight out of twelve major thirds pure and all but one of the fifths audibly yet not too disturbingly mistuned. This worked fine with music using chromatic alteration sparingly. But due to major changes in musical style, by the 1630s keyboard composers like Frescobaldi began to seek effects which required an overstepping of such narrow chromatic boundaries. The battle of temperaments that ensued was won in the end by the now standard, equal variety, which allows free modulation through all twenty-four keys at the previously well-noted cost of both much subtle tonal shading between the various keys and the lovely purity of, notably, those major thirds; since consciously made, in part style- and fashion-dependent choices were decisively involved, little if anything about this outcome may count as foreordained. From the start in the 1630s, adherents to one or another variety of quantitative-experimental science joined in the issue, some (like Mersenne) restricting themselves to calculating a huge range of conceivable temperaments, others looking for more creative, also mathematically elegant solutions. Among the latter was Christiaan Huygens, who discovered that the values for the mean-tone intervals turn up, with negligible differences, in a regular 31-tone tuning — produced by taking, not 11 times the mean proportional between 1 and 2, as in equal temperament, but 30 times — which he calculated using logarithms. This way the strong points of mean tone temperament are of course preserved, and in order to make easy transposition feasible Huygens invented a 'mobile keyboard' which he claimed to have been admired by 'great masters' in his Paris days, yet the principal issue — how to use more than five chromatic alterations apiece — was not even touched by his proposal. Nor did any contribution from the side of mathematical scientists ever affect the ongoing battle in any way — for all the possible clumsiness of their calculations, men of musical practice in their trusted trial-and-error ways had a far better sense of the kind of workable compromise here required. Huygens' contempt for the author of the first 'well-tempered' tuning for keyboards to find wide-spread adherence, the organist Andreas Werckmeister, as "devoid of erudition, and of little worth" points toward one significant, at once social and intellectual aspect of the gap between mathematical science and the crafts here in full view —a social distance too large to make much meaningful communication possible.

We consider next the two pioneers of a radically transformed philosophy of nature, Beeckman and Descartes. Beeckman followed the ancient atomists in taking sound to be made up of a succession of particles emitted by the sounding body. On how this comes to pass he was a good deal more specific than they had been, in that he assumed the vibrating string to cut the ambient air into tiny globules sent off due to the force of that string in vibration (with pipes, whether in wind instruments or in throats, he pointed at sharp edges near the hole where wind enters for the cutting, and at the resulting increase of inside air pressure for the globules' ejection). While associating loudness with the amount of globules (or with the density of their aggregate), he attributed pitch alternatively to their speeds or to their sizes, in such a way that a string twice as short as an otherwise equal one cuts off twice as rapid globules, and/or twice as small ones. Consonance comes about as follows: In moving to-and-fro, the string at mid-way cuts off its maximal number of globules, whereas at the points of return from 'to' to 'fro' and *vice versa*, which provide moments of 'intermediate rest', no globules are cut off at all, so that at each given length of the string each note is not only marked by a definite pitch but also by a sound-silence pattern of its own. In musical intervals, then, the more often such momentary 'sounds' coincide with 'sounds' and momentary 'silences' with 'silences' (as they do all the time in unison; every second time in the octave, etc.), the more consonant the interval is. The table of degrees of consonance that follows from this, however, requires correction, no different in this regard from the corresponding coincidence theory of consonance. Well aware of the need to correct them, which he did principally by invoking the phenomenon of sympathetic resonance, Beeckman saw in addition that tiny, at first unnoticeable irregularities in the production of consonant intervals may, on ongoing reiteration, make themselves heard to the increasing detriment of the consonant effect. Originally no more than a theoretical consideration of Beeckman's, he found it to be musically relevant when confronted by an organist of his acquaintance with the phenomenon of beats, which he went on to explain along these particular lines, concluding in the end that beats come down to coincidences getting out of sync, innocuously so if occurring, say, every 50th cycle, but causing dissonance if taking place much more often.

On being similarly confronted with Mersenne's discovery of a range of harmonics, Beeckman gave as his instant explanation that "a string, by its tremor dispersing the air, breaks it into nearly equal globules; however, as all parts of the string tremble equally frequently indeed, but not equally fast, and as some particles of air are perhaps more fragile than others, and as the thickness of the string is not everywhere exactly the same, it happens that a certain amount of those globules is broken into two, three, four, etc. parts. Those that are broken in two represent to the ear the *octave*, because in the same time it is affected by a doubled sting,"and similarly so for the higher partials.

The 'sting' just mentioned refers to Beeckman's account of the perception of musical sound. Globules ruffle the eardrum the way a pair of sticks ruffles a military drum. As likewise in such a drum the trembling of the drumhead is transmitted through the air inside the drum to the bottom membrane, just so the ruffles on the eardrum are passed on in the same order through the air in the middle ear (and also through the three ossicles co-vibrating with it) to the oval window. At that point (which is as far as Beeckman's advanced yet not quite up-to-date knowledge of the anatomy of the ear went) the auditory nerve takes over, and passes the vibrations on to the brain by means of very fine, material 'spirits' moving either through the nerves or alongside (just as water may stream both through a conduit and alongside it). Pitch differences are faithfully reproduced by these spirits, which contract or dilate in accordance with the fine-ness or coarseness of the original globules, with particularly fine globules that way causing the spirits of the brain (the center of our sensation) to be stung likewise. Generally speaking, whether musical sound affects us sweetly or not depends on whether or not the globules "correspond to the pores of the brain, or of the members, or of the collection of spirits." Note that in this account the sweetness of the consonances, as well as their underlying, numerical ratios, has been lost sight of.

Meanwhile his one-time friend René Descartes, in awareness for the most part of Beeckman's private notes on the subject, dealt with these same issues in accordance with the same explanatory principles applied mostly in different ways. Instead of Beeckman's globular conception, which he dismissed as just "ridiculous", he regarded sound as a succession of vibrations of the air, with their frequency determining pitch and the amount of agitated air their loudness. The propagation of sound through the air takes place by way of wavelets, of which Descartes showed how the successive rarefactions and condensations of the air brought about by the vibrations of whatever object give rise to them. Consonance went explained by him by means of the same 'coincidences of strokes' Galileo was to put forward in his *Discorsi*, and to which Beeckman's account, if shorn of its globules, reduces as well. Descartes dealt in rather a different way than Beeckman with the array of anomalies the consequent table of degrees of consonance appears to call up. Descartes' and Beeckman's accounts of perception of consonant sound also differ, yet not nearly as much as their distinct points of departure, in air globules and in trembling air, respectively, might lead one to suspect. Descartes similarly invoked the nerve ends (which, unaware of the oval window, he thought situated right beyond the third ossicle) being touched by a trembling of the air passed on and kept in vibration from the eardrum to the ossicles, which is where the auditory nerve takes over. With Descartes, no spirits run up hollow conduits to reach the pores of the brain. Rather, the trembling movement, in touching one filament among several which together fill up the nerve, causes that tiny thread to be pulled and thereby to open pores in the brain which release animal spirits of a likewise material nature, and this accounts for the sensation of hearing. Note that, likewise, the sweetness of the consonances and the numerical order of their ratios have in course of the account got lost sight of.

Characteristic of both natural philosophers is the highly speculative nature of their respective treatments. Derivation from first-principles, rather than mathematization of the known or a fact-finding experimental search for the unknown is their prime objective. The range of known phenomena is duly surveyed and, when experiment-oriented thinkers like Mersenne bring new phenomena to the philosopher's notice, these are duly taken up in the explanatory mechanism as well, yet no active search for phenomena as yet unheard of is being undertaken, and possible empirical counterevidence comes up only so as to be brought in line with the main explanation already rendered. What has changed in this particular act of revolutionary transformation is not the knowledge-structure of natural philosophy as such, but the sheer range of phenomena now covered. Ancient atomism had dealt only in the broadest and most summary fashion with the production and propagation of sound, regarded as the emission of particles of various shapes, from smooth to rough. With the focus not so much on the particles themselves any more as on their movements, the explanatory range has vastly increased.

It has so in regard of the amount of phenomena up for explanation and of the level of detail reached, but also in terms of the variety of possible explanations. However restricted the primary entities that alone go into the explanation may look at first sight — the motions of subvisible particles differing in nothing but size, figure, and configuration — the degree of freedom left by these first-principles actually appears to know no limits, and the plasticity of the doctrine is really endless. Sound may consistently be held to be either air globules emitted or air tremblings propagated like waves; sensation may consistently be due either to material spirits streaming up hollow nerves or to fine nerve-filaments being pulled down; what check, given the subvisibility of all these particles and their movements, is there upon such explanations? Briefly said, there <u>is</u> no such check. This was characteristically different in the <u>third</u> revolutionary approach to nature to be considered, which was fact-finding experimental.

As investigated in depth not by me (Floris Cohen) but by me (Penelope Gouk), what turned musical instruments into scientific instruments of a fact-finding kind was the advent, in a mostly Baconian setting, of research into sound for which they came to supply numerous data. Francis Bacon in his *Sylva sylvarum* sought to encourage the creation of an empirical, also useful science of sound by listing two hundred experiments on the subject. Of these, many were actually cribbed from elsewhere, more often than not from the natural magic tradition; many were proclaimed in urgent need of being undertaken, and all together went crowned by an appeal to future Baconians to go to the artisans and find out from their expertise how properties like pitch or loudness vary with material or shape or dimensions of musical instruments. None of this proved in subsequent decades to have fallen on deaf ears. Thus, in the 1640s one early Baconian, Edmund Chilmead, who adopted the 'natural history' mode of research to the letter, sat down to correct factual mistakes Bacon had made on the subject. He also pointed out that in the meantime Bacon's wishes had in effect been fulfilled in Mersenne's *Harmonie universelle*. Here Mersenne had collected, experimentally supplemented, supplied with some degree of order, and where possible enveloped in some moderately quantitative theorizing such trade rules as he had found makers of the most varied musical instruments, from viols to bagpipes or drums, ready to share with him. We have already considered the kind of issues the church organ aroused with him; elsewhere in *Harmonie universelle*, amidst hundreds of pages marked by his congenital conceptual vacillation alternated with sudden flashes of striking insight, Mersenne listed such feats as his painstaking measurement of the speed of sound, or of the upper and lower limits of audible sound, or of the number of vibrations a string actually makes to produce a given note (in other words, of absolute pitch); further, his discovery of a range of harmonics never before distinguished in a musical note; his investigations into properties of natural tones and beats, and, most significantly of all, the outcomes (soon known together as 'Mersenne's law') of his sustained, experimental investigation of the variables (tension, length, thickness) on which the vibrational frequency of a string and, therefore, pitch depends. Another big book aimed at covering the whole of musical theory and practice the experimental way was Kircher's *Musurgia universalis* of 1650. Much more so than with the resolutely anti-magical Mersenne (who, far from denying the possibility of magic, feared it, for religious reasons mostly, to the point of obsession) did Kircher's book display the extent to which phenomena of sound had been enveloped in the context of natural magic on which Bacon, too, had drawn all the while seeking to reform it. Whereas Kircher described in his book numerous experiments of his own, the significance these were in due time to gain for the advance of experimental knowledge was to run chiefly through Part 2, 'Acustica', of a *Magia universalis* he had his pupil, Father Gaspar Schott SJ, compose from mostly his own material. Published in 1657–9, this book went at length into topics like the echo, or analogies between sound and light, or how naturally and artificially produced sounds are related. All this made a profound impression upon numerous investigators in Britain, where whole arrays of experiments on sound were either undertaken or at least contemplated which go back in good part to either Bacon's program or Schott or both.

Among those actually undertaken, most were carried out, in a fitful manner dependent chiefly on whether or not the ruling president was himself a music lover, in the weekly sessions of the Royal Society; where possible, these were then linked up either with chances for use in practice or with general issues of vibrational motion. Others were executed in private only by the Society's Curator of Experiments, Robert Hooke. To mention a few examples, in one session of the Royal Society Hooke brought up test models for an 'otacousticon' (a hearing aid); in another he and Christopher Wren showed that, if you set water in a glass into motion by means of a viol bow, wave patterns occur on the surface in neat correspondence with the pitch of the sound the bow is made to produce at the same time. Further, the Royal Society received report of the unwitting rediscovery, by two musicians, of what Chilmead had found half a century earlier, to wit, that those enigmatic harmonics first distinctly heard by Mersenne arise from the string vibrating in several modes at a time. Paper riders placed on a string in vibration appeared not to be thrown off at certain points later to be called 'nodes'. And by the end of the century Francis Robartes, in a contribution to the Royal Society's journal *Philosophical Transactions*, revealed the connection between these nodes and the multiple vibration of a string, on the one hand, and the range of natural tones of a trumpet, on the other.

By the end of the century, then, a huge amount of data on properties of sound had been assembled at a variety of places and in a variety of contexts. A distinct discipline of acoustics had not yet come into being, however. This was due in part to the aura of natural magic still around it, which experimental scientists tended to disavow without making much of a difference in their experimental practice, and which was not conducive to digging deeply into possibly underlying mechanisms. More importantly, the one unifying theme to hold the various parts of 'musica' together previously, the problem of consonance, had been central indeed to the process of turning the *mathematical* science of music realist but (as Bacon had perceived) was not fit to serve as a unifying theme for the fact-finding, largely instrument-driven science of music of which we have just been discussing the post-Bacon unfolding. Moreover (and let me record in parentheses that on this point my present mouthpiece, Penelope Gouk, differs from me over whether the bottle was already half empty or still half full); moreover, then, the larger unity of which the problem of consonance itself had been a part, to wit, the hoary, commonly accepted idea of the whole of music (theory as well as practice) expressing the harmony of the world had meanwhile been replaced in good part by a conception of music as an aesthetic phenomenon in and of itself — from music as a reflection of cosmic harmony toward music as aimed, above all, at the sensual moving of human affects like joy or mourning or a sense of sublimity. The once close bond between music making and the buildup of the cosmos had been broken; no unifying theme was to present itself for a long time to the investigation of phenomena of sound, contributions to which thus continued to be scattered over a variety of budding disciplines until Helmholtz came along in the 1850s to bring them all together.

So much for a survey, however crude, of how the Scientific Revolution intervened in musical history to turn the instruments of music, so freshly emancipated from the human voice, into something else in addition — into instruments of natural inquiry. In conclusion, I wish to elaborate briefly upon two issues already touched upon. My main subject has been the disruption, at least half-completed by the end of the 17th century, of the harmonic world. I have sought to show how the musical instrument was in good part responsible for the event. In its original capacity, as an instrument of music making, it proved to carry with it a tuning problem not readily soluble inside the frame circumscribed by the consonances upon which alone cosmic harmony could rest. Such gnawing at the edges of cosmic harmony might or might not in the end have led to its ultimate demise. But what then came to speed up the demise by giving the development inside music an entirely unpredictable twist was a surprise event from the outside, the onset of the Scientific Revolution. Each of its three principal strands worked to rob cosmic harmony of its tacitly accepted underpinnings, doing so chiefly by means of approaches to nature incompatible with the conception of number up to then taken for granted in the totality of human thought. In helping destroy cosmic harmony, the musical instrument thus became a source of genuine insight into sound regarded not as an abstract entity but as the very body of music in theory no less than it had always been in practice.

To this main subject of my lecture there has been a countersubject, to wit, the difference between a *theoretical* and a truly *practicable* solution to a practical problem. The question is whether, in 17th century musical science, the gap between them was overcome or not or at least not yet. For the case of temperament we have seen that it was not — elegance of mathematical solutions was one thing; a temperament capable of dealing with a widening range of chromatic alterations, quite another. And so it was in almost every case where, in course of the Scientific Revolution, the budding new science was invoked to solve a practical problem. In this respect, even by the end of the century the craftsmen were far ahead of the scientists. For instance, the discovery of harmonics and of the multiple vibrations that produce them neither did nor could affect the time-honored rule-of-ear manner in which organ builders had already for some two centuries been unwittingly employing them in mixture stops. Or take the great hopes Bacon entertained to achieve, and then to employ for useful ends, the artificial 'majoration' of sound that was a staple of the natural magic tradition. His pertinent concern was specifically with speaking trumpets, 'ear spectacles', echoes, and whispering galleries as known cases to make sound louder and/or carry farther. Activities undertaken in course of the century, by Kircher and by certain Fellows of the Royal Society especially, to enhance understanding of how such phenomena or devices worked, remained scattered and almost entirely inconsequential. Two speaking examples may suffice. Hopes that an increased understanding of sound attained the experimental way was to yield principles sufficient for optimizing the shape of the 'otacousticon' (called 'ear spectacles' by Bacon; really a device for making the deaf hear better) actually came to nothing. Just a tiny bit more successful were efforts to adapt the optimal shape for 'speaking trumpets' (megaphones of sorts) to ideas concerning the reflection of sound in a tube, leading not only to experiments with correspondingly designed instruments, but also, in the end, to some being actually purchased by the British navy. Still, as we all know, the Baconian promise has in the end been fulfilled on the truly grand, really global scale. As in my forthcoming book I seek to demonstrate for the full range of practical issues covered by scientists and craftsmen of all stripes in course of the Scientific Revolution — fulfillment began in the 18th century, not to acquire full momentum until the Industrial Revolution gained pace in the 19th. As I have learned from Penelope Gouk, whom I wish to thank for her willingness to take upon herself a task now nearly fulfilled, in the *Philosophical Transactions* of 1684 Narcissus Marsh, in faithful conformity to that

Baconian promise, envisaged the future construction, by means of the acoustic knowledge meanwhile assembled, of instruments of a new kind, which he dubbed "microphones". These, he confidently announced, will be "contriv'd after that manner, that they shall render the most minute Sound in nature distinctly audible, by Magnifying it to an unconceivable loudnesse". The present state of a civilized world replete with city blasters of meanwhile all-too-conceivable loudnesse testifies to the long-term, everyday significance of those developments in musical acoustics, the origins of which you are now on the verge of jointly exploring. As you proceed today and tomorrow, I wish you all a very good time.