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Flow acoustical determinants of historic flue organ pipe voicing practices

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ABSTRACT

Pipe organs sound differently depending on the regional and contemporary circumstances of their genesis. In order to adequately conserve them it is important, due to the scarcity of sources providing direct information on the building process and particularly on pipe voicing practices, to be able to specify as much as possible the factors that determine their sound signature. To this purpose an organized overview of some of these practices is proposed as a starting framework, exposed with reference to the classical flow-acoustical flue pipe models developed by, among others, Cremer & Ising, Coltman, Elder and Fletcher. On the other hand, a method is presented to assess the tonal and musical effects of voicing configurations, using a 'voicing jack'-like system featuring a complete stop rank of experimental pipes with electronically controlled, continuously variable flue, mouth and toe hole geometry. On this playable system the voicing (and tuning) of the pipes can be varied easily, rapidly, precisely and reversibly. In order to characterize specific voicing strategies both approaches are combined by relating the musical significance associated with the test voicing configurations to corresponding values of a set of characteristic dimensionless ratios. Well-known voicing methods like open or closed toe and over- or underblown voicing are identified accordingly, as well as less common or builder specific procedures.

INTRODUCTION

A better understanding of the operation of organ pipes can be of considerable help in developing better conservation strategies of historic pipe organs. Although differences in tonal performance between instruments from different regions and builders are easily perceived, it's more difficult to track these differences down to the material evidence. Pipe voicers traditionally are experts in just a few particular styles and feel uncomfortable and ignorant outside of these. On the other hand, physical and acoustical analysis of flue instruments operation is more involved with fundamental operating mechanisms and their modeling, and less with the esthetics involved with the differentiation of the model parameters. This paper , which attempts to give an overview of the great variety of historic flue organ pipe voicing practices as found in different regions and periods, does so by combining elements from both worlds. A double approach will be used: voicing practices will be described in terms of the classical flue instruments physical descriptions that have been developed ever since the XIXth century, with particularly important progress in the 60's, 70's and 90's of last century. Specifically, a number of dimensionless parameters will be selected with which voicing practices will be classified. And on the other hand, because the sensible ear remains a valuable measuring device in correlating or distinguishing sounds, an experimental setup will be presented which focuses on the perceptive and esthetic qualities of voicing schemes. This approach might make up for some of the difficulties encountered in trying to identify with confidence certain sound qualities in the extant historic evidence.

The scope of this paper is limited to flue organ pipes, more specifically the so-called medium-scaled (open) principals which form the heart of every organ. Attention will be given mainly to the voicing practices associated with the mouth region, thus excluding influences of:

- various tuning devices near the open end
- wall material and thickness and surface finish
- upper labium geometry
- languid edge geometry
- nicks
- wind supply transients
- various ear and roller beard geometries

BASIC VOICING PRINCIPLES

Determinants of flue organ pipe voicing

Although pipe organs seem to have a common origin, going back to the Greeks, by the end of the Middle Ages, when they seem to have been firmly established all over Western Europe [Williams 2005], differences in climate and society culture inevitably led to differentiation in organ design. They were mainly conceived for the churches, first for the smaller and less reverberant Roman, later for the large stone-and-glass Gothic edifices. Accordingly they seem to have had to produce rather large sound volumes, as testified by the early appearance of the Blockwerk, which by the simultaneously sounding many pipes per note of widely differing pitch (superoctaves and -fifths), fully took into account the masking properties of the ear. In this period they all had in common the use of low wind pressure and flow rate, because of economies of number of necessary bellows and man-power and less problems with leaks which tend to get worse with increasing pressure.

Low wind pressure has more advantages:

– Lower action force necessary

- Easier to voice because irregularities tend to be smoother.

Disadvantages however were:

- A less powerful sound, countered as much as possible by the 'widely different pitches' principle
- Attempting to minimize air consumption meant voicing with narrow flues, so that it's more difficult to obtain both equalized loudness and timbre throughout the range
- Dust accumulation in narrow flues disturbs operation
- The loudness and brilliance of reeds suffers particularly

Accordingly the early pipe organs, like the Blockwerk, minimized wind consumption by:

- using a 'synthetic' tonal design which not necessarily contained reeds
- implementing relatively weak basses (often with short octave)
- using open foot and narrow flue voicing

The gradual evolution towards organs with more 'gravitas' is thus another demonstration of the close interaction between esthetics and technology.
Voicing practices, as was every part of the organ design, were also determined by the intended use of the instruments. In Italy and France the organ served to embellish the liturgical service, for instance through the alternatim practice. In the former country the organ was treated rather as an alternative to the voice, in the latter is was precisely supposed to provide a contrast to the sung parts. With the advent of the Lutheran church in Northern Germany an instrument capable of accompanying the community singing was needed. Besides these liturgical conditions the sound of the organ was also impregnated with the treats peculiar to a people's culture: the classical French organ reflected the splendor and wealth of the Sun-king's court, the North German organ the order and multilayered-ness of this society consisting of Church and State, patricians and peasants.

The fundamental voicing laws

Certain voicing laws seem to be universally applicable and find their equivalents elsewhere in music practice. Before turning into the details of pipe voicing adjustments it's interesting to briefly mention some of the more widely accepted of these laws and possibly try to interpret them from an acoustical viewpoint.

In highly reverberant rooms bass notes are favored

In accordance with the rule of thumb, that the longest (open) pipe of the organ should fit about 16 times in the largest distance the sound can travel uninterrupted, the ability of a sound wave to perform sufficient reflections seems to sharpen the aural attention to this frequency. In small rooms this becomes difficult for low frequencies and they are perceived with less acuity than the treble sounds. This phenomenon is possibly one of the main reasons why the organ became so successful in the church: with reasonable input of resources it turned out to be possible to create huge soundscapes, mainly produced by myriads of little organ pipes and adequately supported in the bass by a limited number of reasonably large pipes.

The bass notes need stronger harmonic development than the treble

This law, which is clearly related to the frequency dependent sensitivity of the ear, ensures that low notes are sufficiently present to the auditor through the presence of some of their higher harmonics in the most sensitive frequency range. It's a universal law found in virtually all musical instruments designs. Evidence of its presence in any organ stop is found in the geometrically non-similar progression of scales, with diameter halving occurring at the 16^{th} to 18^{th} pipe instead of the 13^{th}.

Quick voicing opposes rich timbre

Another law which is reminiscent of similar observations in other instruments, like in strings or percussion. As to its relevance in flue organ pipe voicing, it will be studied further in conjunction with the jet angle parameter.

FLOW-ACOUSTICAL DETERMINANTS OF FLUE ORGAN PIPE VOICING

Introduction

In this section a set of dimensionless parameters is defined, by means of which an attempt will be done to characterise various voicing practices. They are based on the classical models of flue instrument operation that have been developed since the 1960's. A thorough evaluation of their validity and utility, by means of extensive measurements on the variable mouth geometry pipes set, will be the subject of future reports.

Inharmonicity parameter D_{inharm}

The inharmonicity of the passive pipe resonances is determined by the ratio a/L, where a is the pipe's radius and L its length, and the ratio of pipe cross-sectional area to mouth area $S_{openend}/S_{mouth}$. a/L can equivalently be written as $S_{openend}^{1/2}/L$, so that combining both leads to the introduction of the inharmonicity determinant:

$D_{inharm} = S_{openend}/(S_{mouth}^{1/2} L)$

Because the end corrections increase with increasing a, and are smaller for the higher resonances, wider pipes and pipes having small mouths will sound less rich than narrower pipes. Accordingly, because their radiated acoustic energy is spread over a larger spectrum the latter will therefore tend to sound louder. On the other hand the sound of the former, with their acoustic energy more concentrated in the very first harmonics, will carry a larger distance.
Establishing this determinant for a pipe register constitutes a fundamental problem in pipe organ design, the goal being to find a row of pipes which is sufficiently balanced in loudness and timbre throughout its range. Assuming a to scale like f^{-x} and with the usual pipe geometries, an equalized loudness level throughout the range can be obtained when x varies from .87 to .67 going from bass to treble [Fletcher & Rossing 1998, Steenbrugge 1997]. These values lie around the so-called normal scale with x=.75.
As both the mouth [Ingerslev & Frobenius 1974] and open end corrections [Levine & Schwinger 1948] scale with a in pipes with the usual proportions, D_{inharm} scales like f^{1-x}. This implies that only geometrically similar pipes, with x=1, will show the same resonance positions relative to their respective sounding frequencies and their harmonics. As a result, the requirement for balanced loudness will tend to make the bass pipes narrower and thus more harmonically rich, in accordance with psycho-acoustics and the corresponding fundamental voicing law.
D_{inharm} has a range as much as between 10^{-2} for very narrow large mouthed pipes, and 10 for very wide pipes with small mouths.
The position of the harmonics of the sounding tone with respect to the shifted passive pipe resonances leaves the possibilities that both more or less coincide over specific frequency ranges, thus possibly creating formant structures in the sound spectrum.

Pipe resonance quality factor D_Q

This determinant describes the peak values of the pipe's resonances and is given by:
$D_Q = f_r/\Delta f_r$
where f_r is a resonance frequency and Δf_r the 3dB bandwidth around f_r.
For high Q resonators, such as organ pipes, D_Q at f_r is also equal to:
$D_Q = 2\pi f_r$ * Energy stored / Power loss
The energy stored is proportional to a^2Lv^2 and the power loss assumed to mainly result from turbulent losses, which are proportional to kinetic energy multiplied by flow rate, or a^2v^3. As a result, D_Q is proportional to v^{-1}, and because for the usual pipe geometries v turns out to scale like $f^{(1-x)/2}$ [Steenbrugge 1997], this discussion seems to imply that equalized timbre throughout the pipe rank by keeping the quality factors constant is possible only when x=1, so with geometrically similar pipes, which turns out to be the same condition as with D_{inharm}.

Jet transit time to oscillation period ratio D_{mouth}

This ratio is defined as:
$D_{mouth} = fl/V$
where f is the frequency of the first harmonic of the pipe oscillation, l the cut-up, and V the jet velocity.
This parameter fundamentally influences the feedback cycle of the pipe. Changing its value adjusts the phases of the various wave propagations in this cycle, which is accompanied by slight changes in the fundamental oscillation frequency and resulting variations in harmonic amplification by the passive resonances.
1. Influence of D_{mouth} on the optimal operating point:
According to Ising [Ising 1971] the pipe reaches an optimal operating point when the 'Voicing Number' I, defined as:

$$I = \frac{V \cdot \sqrt{h}}{f \cdot l \cdot \sqrt{l}}$$

where h is the flue width and l the cut-up, has the value 2. For this value of I the pipe sounds at the fundamental passive resonance frequency and the first harmonic has the largest possible amplitude. This gives a very dull sounding pipe, a principal-like voicing would require a higher I, by increasing V or reducing l, which would shift the operating point towards an overblowing regime with more presence of higher harmonics (see next point).
In terms of D_{mouth}, the previous formula can be rewritten as:

$$D_{mouth} = \frac{1}{I} \cdot \sqrt{\frac{h}{l}}$$

2. Influence of D_{mouth} on timbre:
The most familiar effect of increased D_{mouth} is reduced harmonic content in the jet drive, due to the jet velocity profile spreading and flattening with increasing distance from the flue [Bickley 1937].
Increasing D_{mouth} moreover decreases the part of the feedback phase cycle assumed by the resonator and thus the feedback period will increase. At the same time the mouth end correction decreases so the lower passive resonance frequencies of the resonator increase. The pipe resonances become more harmonic which will favor the higher and somewhat reduce the lower harmonics. A pipe voiced in this underblown regime is less mode-locked and can more easily adjust to slight variations in wind pressure, therefore its sound is rounder and livelier. An overblown pipe on the other hand has a more limited adjusting range and sounds rich and boosted, on the verge of its resonant possibilities.
The range of D_{mouth} in organ pipes is roughly between 0.1 and 0.25.

Jet angle parameter D_{angle}

The air jet symmetry with respect to the upper labium is another fundamental voicing determinant whose influence on timbre is reported on several times in acoustical and practice-related literature, and which has been theoretically studied [Fletcher & Rossing 1998]. Starting from an outwardly directed jet a slow attack is first observed, together with spurious noises and a strong second harmonic. As the jet gradually moves inwards, the pipe becomes faster and reaches a typical principal character. At a certain point the pipe becomes more fluty with the second harmonic in particular becoming weak. When the jet blows more inwards the tone again becomes more principal-like, a very nice timbre and very prompt, but difficult to stabilize. Immediately after this the pipe overblows [Bormann 1986]. According to this source, metal and loud wooden principal pipes are usually voiced blowing outwards and the slower attack taken for granted, following the rule of thumb 'Quick and dull, slow and bright', or made faster by the use of ears. Sharp sounding wooden pipes and stopped pipes are voiced for fast attack with the wind blowing inwards.
D_{angle} can be defined as the angle between the line connecting the middle of the flue and the upper labium, and the symmetry axis around which the jet performs its back and forth motion. Accordingly it cannot usually be determined from the pipe geometry but needs to be measured with a suitable flow measurement device.
D_{angle} depends on the flue geometry, and for certain geometries also on wind pressure, a fact known since long by organ builders who liked to experiment [Cavaillé-Coll 1895].

Flue to toe hole area ratio $D_{flue/toe}$

Both toe hole and flue area determine the amount of pneumatic power supplied to the pipe. In voicing practice usually one of them is kept relatively wide open and the other serves as the main regulating device. The following parameter characterizes this choice:
$D_{flue/toe} = S_{flue}/S_{toe}$
where S_x is the area of orifice x.
1. $D_{flue/toe} \ll 1$: if one wants to use the maximum amount of available wind pressure the toe holes must be kept wide open and thus regulating the pneumatic power delivered is achieved by adjusting the flue width. In practice adjusting the flue width is more difficult than changing the foot hole, because deviations from the 2-dimensional mouth and flue geometry negatively influence the timbre. Furthermore, changing the flue width usually also changes the jet angle. Accordingly, adjustments of narrow flues can expected to have a strong influence on timbre. Very narrow flues are said to have a 'thin' sound [Dom Bédos 1778].
Altogether open toe voicing is a more difficult technique requiring very delicate manipulations, but allows good power efficiency. Open toe voicing of an organ at its final location used to be a long, tedious and very careful process. The slight irregularities it leaves give the total sound a very lively touch and, together with the variable pressure wind supply by the

wedge bellows, is one of the main features that give genuine old organs their organic character.

2. $D_{flue/toe}$ >>1: Toe hole regulation allows a more flexible and easily controllable foot wind pressure scheme throughout the pipe rank, at the expense of pressure losses across the toe hole. At wind pressures above 80mm [Jamison 1959] the jet shear layers develop turbulence eddies of different scales, translating into a 'frying' sound component unless nicks are applied.

Foot pressure buildup parameter D_{foot}

The main parameters determining the nature and duration of the starting transient of the pipe tone is D_{angle}. However the wind pressure rise time in the pipe foot also plays a role, it mainly depends on:

- wind pressure rise time in the wind chest: barred chests have a slower pressure buildup than unit and/or cone valve chests, therefore pipes intended to be placed on the former can be voiced for quick attack but will tend to initially overblow when put on the latter.
- Toe hole diameter which determines wind supply flow rate Q_{toe}
- Pipe foot volume V_{foot}

Therefore the Strouhal number-like parameter defined as:

$D_{foot} = fV_{foot}/Q_{toe}$,

representing the pipe foot filling time to oscillation period ratio, is suggested to characterize the starting time. This parameter is most relevant for pipes with $D_{flue/toe} >> 1$, which were often placed on fast wind chests and voiced to have a fast attack, through the use of nicks and $D_{angle} \approx 0$.

CHARACTERIZING HISTORIC FLUE ORGAN PIPE VOICING PRACTICES USING THE FLOW-ACOUSTICAL DETERMINANTS

Introduction

The main purpose of introducing the parameters in the previous section is to provide some simple and objective descriptors to characterize the way flue pipes are voiced. They should be sufficiently sensitive to be able to distinguish various voicing practices as they have been in existence in history, possibly even down to individual organ builders and voicers. In the following only a brief overview of some the most influential and widespread historic situations will be given, the experimental evaluation of most of these characterizations is in progress and will be reported on in subsequent papers.

Renaissance Italy

Among the ancient pipe organs still extant and in relatively authentic condition, many can be seen and heard in Italy. The Italian Renaissance organ developed as an attempt to emulate the a capella practices emerging from the Palestrina style imposed by the Council of Trent. It mainly consists of open principal pipework on just one chest and with one keyboard. Wind pressures are particularly low (40-50mm),

Characterization:

D_{mouth}: low cut-up, overblown voicing

D_{angle}: slow attack, as principal-like as possible, jet strongly outwards

$D_{flue/toe}$: open toe, narrow flue

XVIIth century Northern Germany and the Northern Netherlands

Whereas in Italy the singing properties of the fundamental 'Principale' register were developed, with the higher stops merely serving to make the sound more vibrant, in Flanders the principle of synthetic sound was invented, combining various sorts of pipe ranks and scales to produce a whole variety of sonorities. It was the basis for the Northern European organ concepts, allowing to produce great plena with relatively low wind pressure. Transparent rendering of polyphonic music became possible through the use of multiple 'Werke', each with a different tonal composition and each allowing a great many different timbres. Low wind pressure accounted for relatively weak basses and reeds, the latter merely serving to further increase variety in timbres and not to stagger the plenum sound. The concept of 'organ sound synthesis' further accounted for the presence of many different flute pipe registers as well as relatively neutral sounding principals. A typical builder representing this style is Arp Schnitger (1648-1719).

Characterization:

D_{angle}: quick, symmetrical voicing

D_{mouth}: voiced for maximum power

$D_{flue/toe}$: open toe, narrow flue

XVIIth and XVIIIth century France

The Flemish synthetic sound principle also spread to France (and Spain), where it developed into an even more brilliant ensemble than in the Northern countries. Although the principals were also rather neutral, they were topped by delicate mixtures. Besides these the flutes were well represented, especially in the form of strong and bold mutations, some of which, like the Cornet, had their own little windchest. Due to the scaling method, which made use of an 'addition constant' [Dom Bedos 1778], the middle keyboard range was somewhat weaker than bass and treble.

Above all, reeds with very shallow shallots and thin flat tongues were developed which could cope with the medium low wind pressure and nevertheless produce a bright, majestic sound that gave, assisted by the flue mutations in the treble, the French organ its real grandeur. A typical builder is Francois-Henri Cliquot (1732-1790).

Characterization:

D_{angle}: quick voicing

D_{mouth}: optimal to underblown voicing, Dom Bedos recognized that the cut-up is more related to pipe length than to diameter [Dom Bedos 1778]

$D_{flue/toe}$: beginnings of toe regulation, Dom Bedos writes that flue and toe hole areas should be approximately equal [Dom Bedos 1778].

XVIIIth century in Saxony and Southern Germany

The availability of higher wind pressures (90mm) from more efficient wind systems and more accurate and pre-industrial production methods led to a new organ type, characterized by more profoundness and equalization in timbre, all this being introduced by the Saxon organ builder Gottfried Silbermann (1683-1753). He very often used the same scales in different rooms, adapting the sound by adjusting the toe holes [Gress 1989]. He was famous for his 'silvery' principals choirs, obtained by voicing the fifths in the mixtures somewhat quieter than the octaves.

Characterization:

D_{angle}: jet blowing strongly outwards [Lottermoser 1983], and upper labium pulled forward, giving a somber dignity and at the same time a stringlike character

D_{mouth}: optimal power voicing

$D_{flue/toe}$: active toe regulation but still medium flue width, in French tradition, which also accounts for a full, noble sound.

XIXth century France

During the XIXth a whole series of events pushed the organ into a further development stage:

- extended tonality and associated equal temperament fought against mixtures and mutations based on pure intervals, so they disappeared
- the upcoming (symphonic) orchestra gave the impetus to provide more equally pitched (8') stops, with variety in timbre resulting from their combinations
- high wind pressures (sometimes subdivided into lower pressure bass and higher pressure treble) made any loudness possible throughout the keyboard range

With the great builder Aristide Cavaillé-Coll (1811-1899) principals are no longer the sole 8' foundation, other 8' stops of different nature are added and can combine to obtain the famous French 'Fonds', which are softer and more versatile than the English solution which consisted in replicating principal-like registers.

Characterization:

D_{inharm}: use of expressions to tune the pipes, increasing pipe resonance inharmonicity

D_{angle}: in his writings, Cavaillé-Coll describes many flue configurations he uses and the resulting sound qualities [Cavaillé-Coll 1895]. Further research is needed to further characterize these.

D_{mouth}: Cavaillé-Coll did many studies on the cut-up and finally, with his obsession of comparing the moving air jet with the vibrations of reeds, concluded that the cut-up followed the same progression as the tongue lengths in reed pipes instead of being proportional to diameter [Cavaillé-Coll 1895].

$D_{flue/toe}$: consistent loudness regulation using the toe hole

XIXth century England and United States

The Romantic English school borrowed more from the mainland styles than from its own traditional styles, aided by many immigrated builders. One direction (Edmund Schulze and followers), under German influence, favored open toe holes and flues to obtain more power, another (Henri Willis and followers) advocated high wind pressures (>100mm). Nicking universally used. Subtleness in timbre gradually was abandoned in favor of loudness.

Characterization:

D_{inharm}: wide scales, use of expressions to tune the pipes

D_{angle}: maximum power voicing

D_{mouth}: underblown voicing

$D_{flue/toe}$: toe hole or combined toe and flue regulation in order to maximize power without high pressure wind

A VARIABLE MOUTH GEOMETRY FLUE PIPE REGISTER

In order to evaluate many of the above assertions concerning different voicing practices a series of flue pipes was build which allows to vary the following geometrical parameters:

- cut-up, realized by vertical movement of the upper labium
- relative position of upper labium with respect to the flue, this is accomplished by dividing the resonator part from the foot and flue part, and allowing a relative translation of both in a direction perpendicular to the flue
- flue width, by horizontal movement of the languid
- toe hole width, by horizontal movement of a slide inside the foot covering the toe hole

The following picture shows one of the pipes. Visible are the upper resonator part sliding on the lower foot, and the step-motors and controllers driving the linear movement actuators.

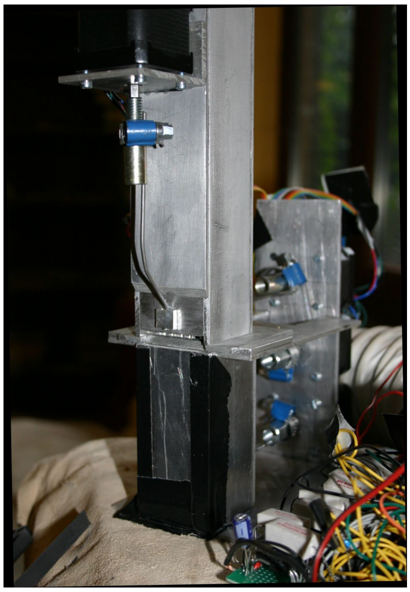

Illustration 1: Variable mouth geometry flue pipe

The pipes have a square section and are made from Al with wall thicknesses between 2 and 4mm. The front of the languid and the lower labium are exchangeable to allow different flue configurations. The moveable parts are connected to linear actuators driven by step motors, the displacement step unit is 5µm. The step motors in turn are computer controlled so that exact displacement distances can be preprogrammed. All actuators have a hard-wall stop position which the stepping motor driver circuit can detect from the current consumption, so all displacements can be easily calibrated. All this allows to define and accurately reproduce specific configurations.

In order to evaluate the musical quality of specific voicing settings, a complete register of pipes like this needs to be built. However, using sampler software it is possible to start with a limited number of pipes, record the note they play and use pitch shifting and sound morphing algorithms to reconstruct the sound of the missing pipes. A pressure transducer will be connected to the wind chamber to monitor pressure. The resonator is made up of stacked pieces which can be manually removed in order to modify the pipe scale.

Preliminary tests with this system reveal the enormous difference in evaluating voicing modifications to one single pipe and the same modifications to a musically meaningful set of pipes. They suggest that easily perceivable differences in the musical qualities of various pipe ranks can be the result of really small voicing adjustments and that the goal of characterizing differently voiced pipes must be realistically pursued.

CONCLUSIONS

An brief overview was given of historic flue organ pipe voicing practices. A method was proposed to characterize those practices by means of flow-acoustically relevant parameters. The usefulness of this approach is now under test by collecting data from historic pipe organs and trying to imitate the voicing adjustments detected using the variable mouth geometry pipe system. Experiments will also show whether, within the aforementioned limits of this study, additional determinants are significant, for example to account for the influence of jet velocity asymmetry, vortex shedding near the upper labium, specific pipe resonator geometries,...

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