Chapter 2

Construction and Design

[Is it not] a great irony . . . that when [the] quiet equilibrium [of 18 tons of string tension and 1,000 pounds of downbearing being resisted by the plate and soundboard] is violently upset by a pianist, and when the system is relentlessly struggling to restore its natural calm, the piano is singing.

—Nick Gravagne, RPT

The history of piano design is a history of improving the efficiency of the conversion of the force of a finger to acoustical energy. Piano designers have achieved this by focusing on three aspects of piano design:

- Increasing the tension of **strings** and finding ways to resist the compression they produce
- Increasing the tension and compression in the **soundboard**
- Improving the tension and compression in an ever-heavier **hammer**, and improving the efficiency of the action to support the hammer

By around 1870, within a century and a half of the piano's development, improvements in these areas had made the piano suitable for ever-larger theaters and music halls.[111] No longer just a chamber instrument, the piano became capable of carrying a solo part against an orchestra of over a hundred musicians.

More recently, designers have experimented with stiffer materials for the soundboard and action parts, which improve the efficiency of energy transfer. Richard Dain of Hurstwood Farm Piano Studios, the designer of Phoenix features in Steingraeber & Söhne pianos, points out that the efficiency of energy conversion in a conventional piano is similar to that of a steam locomotive—about 4%—whereas it is up to 8% in pianos equipped with carbon-fiber soundboards, carbon shanks, and bridge agraffes instead of the conventional bridge pins.[112]

[111] Steinway's famed 14th Street Hall, built in 1866, seated 2,500. See D.W. Fostle, *The Steinway Saga*, p. 43.

[112] See "Sound Quality and Power" at `http://www.hurstwoodfarmpianos.co.uk/news.php?news_id=13`.

Overview of Construction

The foundation of the piano consists of the **rim** (or a wooden frame in verticals), the **beams**, and the **belly rail**, which are assembled into a strong structure (Figure 30).

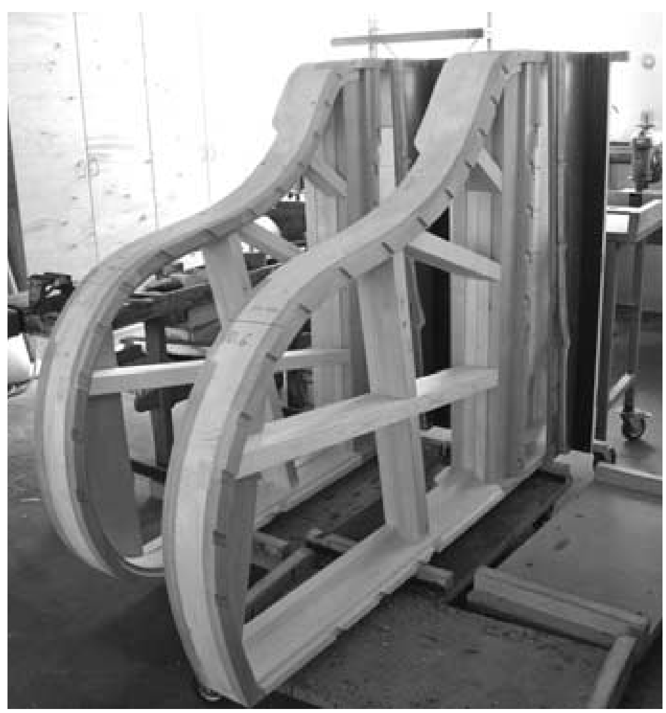


Figure 30 *Grand piano rims with beams and belly rails (Bösendorfer factory).*

Figure 31 *Installed grand soundboard with bridges (top) and plate (bottom) (Bösendorfer factory).*

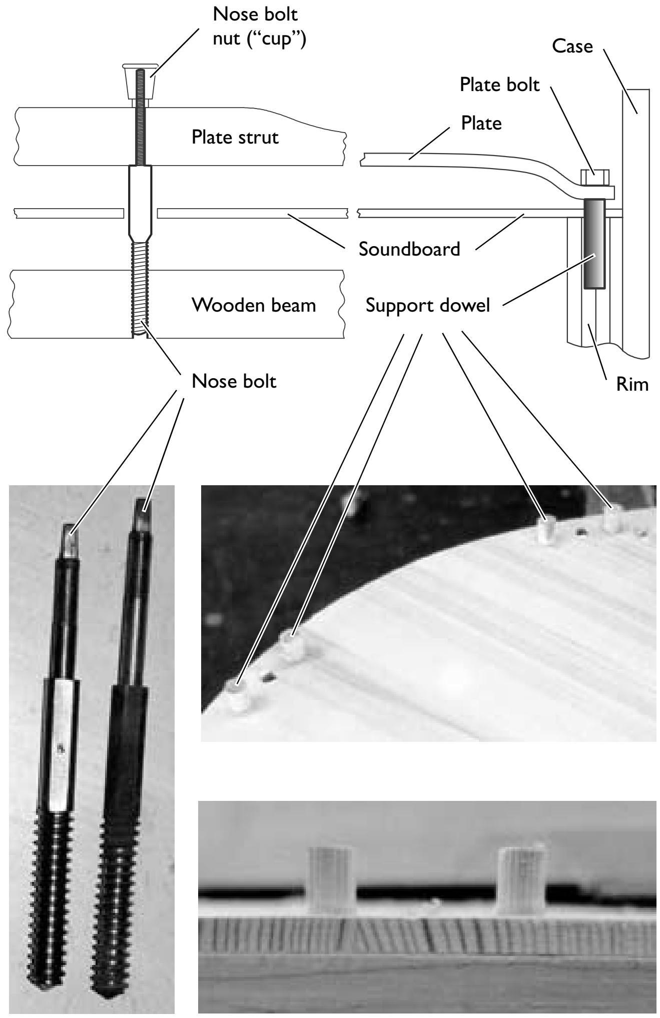


Figure 32 *Piano plate supports: nose bolts and rim dowels.*

In the best grand pianos, the **pinblock** and the **stretcher** are also parts of this structure as they are mortised or doweled into the rim. The **case** may be built together with the rim in one procedure, or may be added to it later. In grands, the **key bed** that is glued to the underside of the rim serves as additional structural reinforcement.

In grands, the **soundboard** is glued throughout its perimeter to the rim and the belly rail, while in verticals it is glued to the frame. It is gently curved upward in the middle to better resist the downbearing of strings (discussed below). This curvature, or "crown," is supported by the **soundboard ribs**: wooden bars that are glued to the underside of the soundboard. The main purpose of the ribs, though, is to increase the stiffness of the board across the grain.

The **long bridge** and the **bass bridge** are glued to the soundboard. Two bridges are necessary because of the *over-strung* (also called *cross-strung*) design: bass strings cross over the tenor strings and have their own bridge. In smaller pianos, the bass bridge often has a **shelf** (also called "apron") that allows bass strings to be longer while transferring their vibrations to the more flexible area of the soundboard.

The cast-iron **plate** (Figure 31) is installed over the soundboard to suspend the **strings**, which are stretched at high tension. The modern plate covers the entire piano and greatly increases its structural stability. It is fastened to the rim and to the pinblock, and does not touch the soundboard. The plate commonly rests on dowels, wooden blocks, or bolts that extend vertically from the rim and pass through the soundboard (Figure 32).

The plate is also fastened to wooden **beams** under the soundboard with **nose bolts**. The bolts are threaded into the beams and extend to the plate through holes in the soundboard. The plate is affixed to nose bolts with large, decorative nuts or "cups." The larger the plate, the more nose bolts are needed to suspend its struts and its horizontal sections.

In longer Steinway grands (models A–D), the rigidity of the plate is increased in the treble section with a bolt that

Myth:	**The Steinway bell amplifies sound.**
Truth:	The "bell" is a massive piece of cast iron that, although hollow, has walls that are much too thick to ring. If the bell did ring, it would introduce its own resonances, and its purpose is to *reduce* resonances by stiffening the plate.

attaches the plate to the so-called **Steinway bell**[113] (Figure 33) through a hole in the soundboard. This massive, hollow casting is firmly attached to the bottom of the rim on the curved side of the piano. By increasing the rigidity of the plate in the treble, the Steinway bell reduces the plate's absorption of acoustical energy (energy produced by strings when vibrating), thus increasing the length of decay and the volume of sound in that section. Since less energy is absorbed by the plate, more of it reaches the soundboard to produce a louder, longer-sustained sound. The rigidity of the plate also is increased with nose bolts and with cupola design (page 56).

The strings are attached on one side to **tuning pins** (Figure 34), and on the other to hitch pins (see Figure 650 on page 424). Tuning pins are inserted into the wooden **pinblock** through holes in the plate, whereas hitch pins are inserted directly into the plate. On the tuning pin side there is a massive flange on the underside of the plate. This flange keeps the pinblock firmly in place and counters the pressure from the strings, which passes through the tuning pins on the pinblock, then on the plate. The plate is firmly attached throughout its perimeter to the rim and the pinblock. In higher-quality grands, the plate is also attached to the metal shoe in the belly rail by one or more plate horns (Figure 36). The horns transmit the pressure that the strings exert on the plate via the shoe to the beams and the rim, which transmits it back to the plate. The strings' pressure, therefore, is not countered by the plate alone, but by the structure of the entire piano.

Strings pass over the bridges, held tightly by the staggered and slanted **bridge pin**s (Figure 35). The bridges transmit vibrations from the strings to the soundboard, which transduces them into sound. To ensure solid contact with the bridges and to improve the amplification of sound in the soundboard, strings exert some downward pressure on the bridges. This *downbearing* is made possible by constructing the bridges to deflect the strings upward (see Figure 645 on page 417).

Each string has a carefully predetermined **speaking length**, a segment that defines its pitch. This segment is terminated on one end by the front bridge pins, and on the other end by one of several possible devices: the **capo tasto**, **agraffes**, or a **raised plate flange**. The capo tasto is

Figure 33 *The Steinway "bell" supports the plate and increases its rigidity in the treble (ca. 1985 Hamburg Steinway model C).*

Figure 34
Tuning pin.

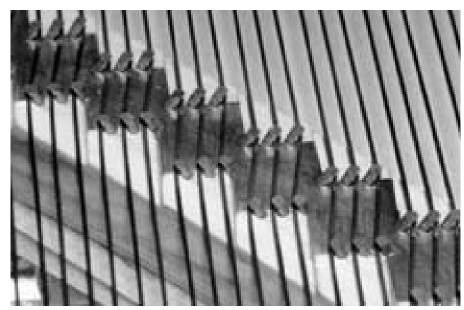
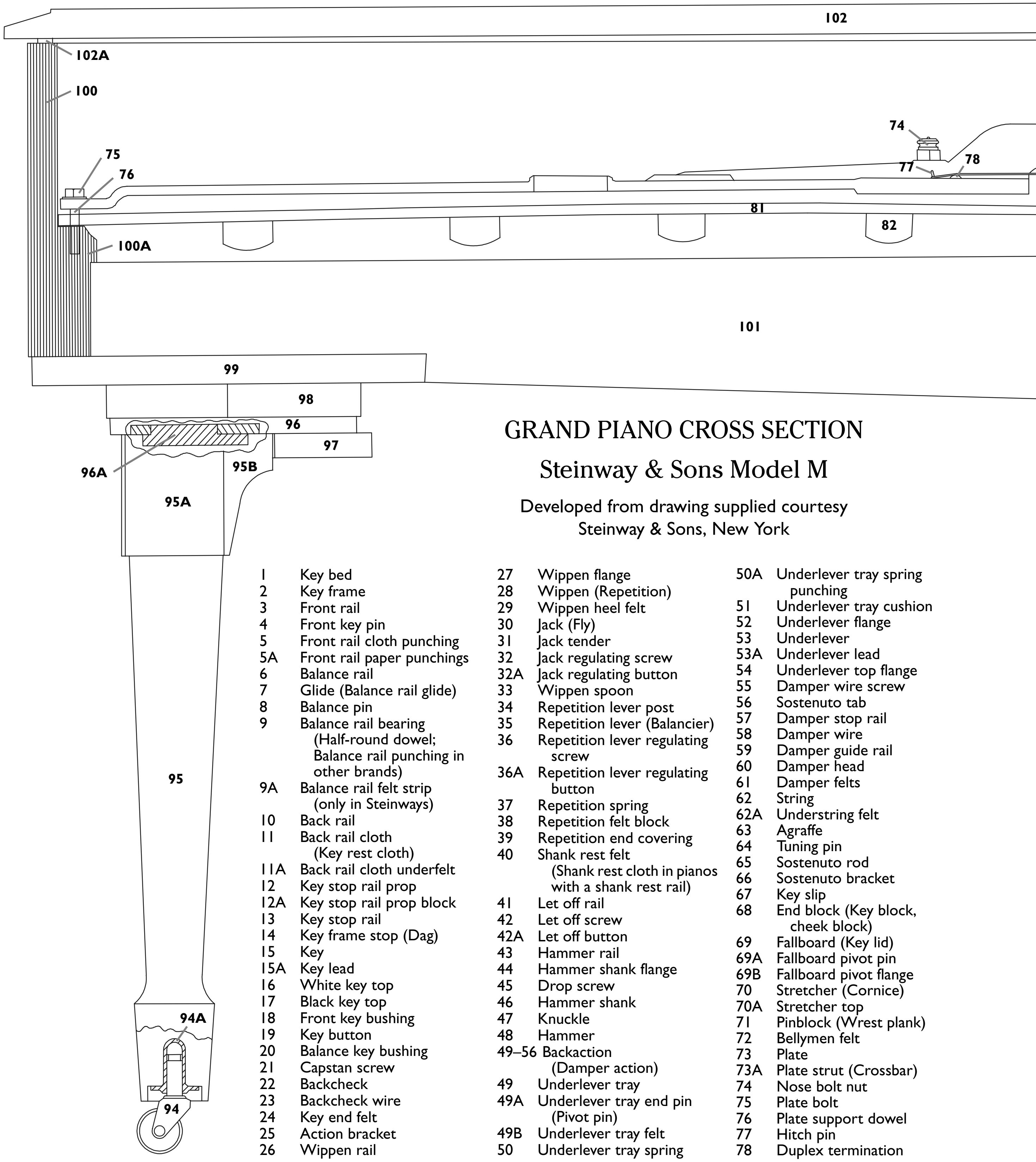


Figure 35
Bridge pins.

Figure 36 *The plate horn in modern Steinway & Sons grand plates is connected by a steel wedge to the metal shoe toe, which protrudes through the belly rail (see Figure 55 on page 29). The beams converge on the shoe behind the belly rail.*

113 U.S. patent no. 314,740 by C.F. Theodor Steinway (1885). In many publications, Steinway's first name is anglicized to "Theodore." I have retained the original spelling of "Theodor" because he signed most of his later patents as "C(hristian) F(riedrich) Theodor Steinway," and also to avoid confusion with his nephew, Theodore E. Steinway, the author of *People and Pianos*.

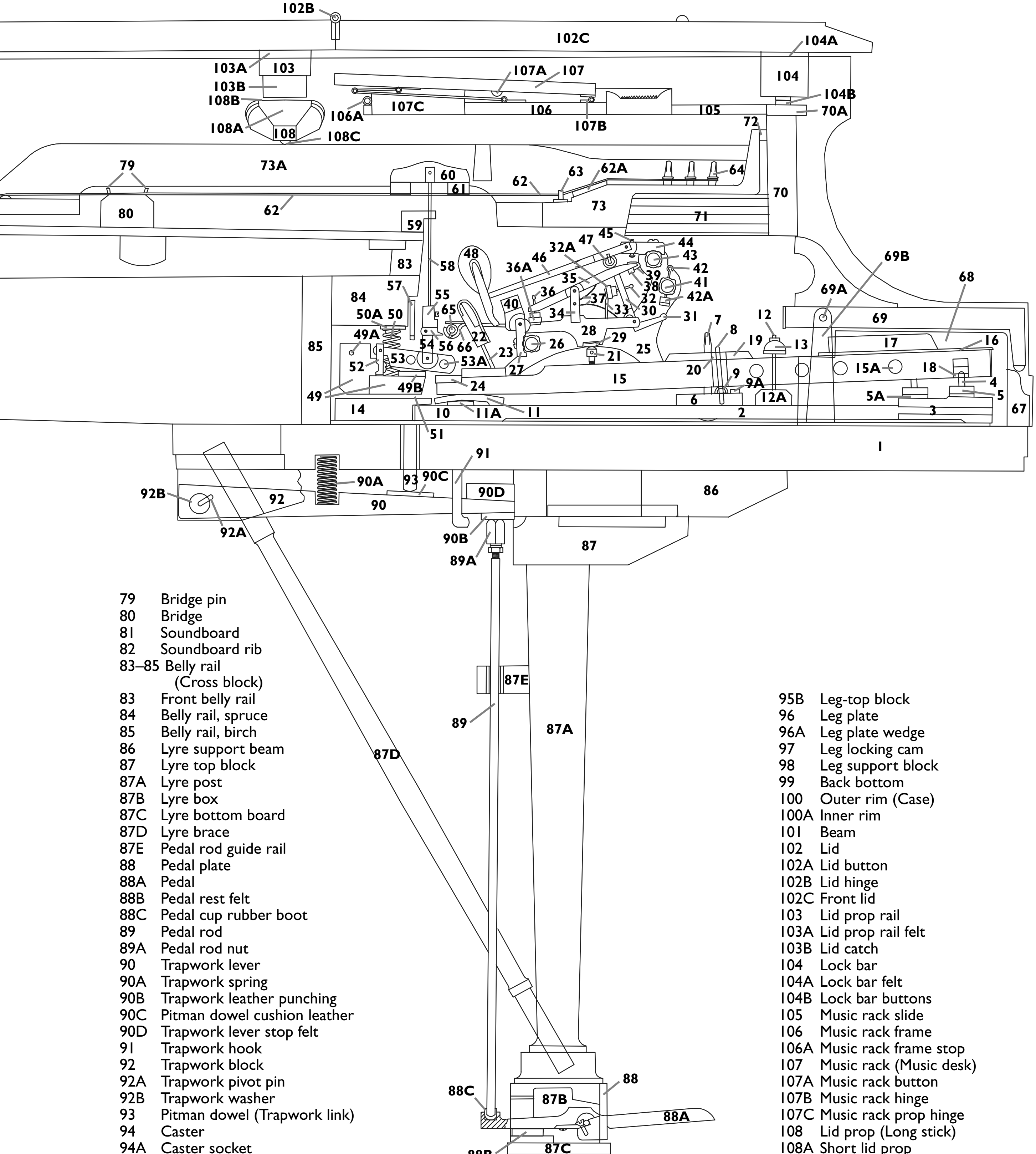


GRAND PIANO CROSS SECTION

Steinway & Sons Model M

Developed from drawing supplied courtesy
Steinway & Sons, New York

1	Key bed
2	Key frame
3	Front rail
4	Front key pin
5	Front rail cloth punching
5A	Front rail paper punchings
6	Balance rail
7	Glide (Balance rail glide)
8	Balance pin
9	Balance rail bearing (Half-round dowel; Balance rail punching in other brands)
9A	Balance rail felt strip (only in Steinways)
10	Back rail
11	Back rail cloth (Key rest cloth)
11A	Back rail cloth underfelt
12	Key stop rail prop
12A	Key stop rail prop block
13	Key stop rail
14	Key frame stop (Dag)
15	Key
15A	Key lead
16	White key top
17	Black key top
18	Front key bushing
19	Key button
20	Balance key bushing
21	Capstan screw
22	Backcheck
23	Backcheck wire
24	Key end felt
25	Action bracket
26	Wippen rail
27	Wippen flange
28	Wippen (Repetition)
29	Wippen heel felt
30	Jack (Fly)
31	Jack tender
32	Jack regulating screw
32A	Jack regulating button
33	Wippen spoon
34	Repetition lever post
35	Repetition lever (Balancier)
36	Repetition lever regulating screw
36A	Repetition lever regulating button
37	Repetition spring
38	Repetition felt block
39	Repetition end covering
40	Shank rest felt (Shank rest cloth in pianos with a shank rest rail)
41	Let off rail
42	Let off screw
42A	Let off button
43	Hammer rail
44	Hammer shank flange
45	Drop screw
46	Hammer shank
47	Knuckle
48	Hammer
49–56	Backaction (Damper action)
49	Underlever tray
49A	Underlever tray end pin (Pivot pin)
49B	Underlever tray felt
50	Underlever tray spring
50A	Underlever tray spring punching
51	Underlever tray cushion
52	Underlever flange
53	Underlever
53A	Underlever lead
54	Underlever top flange
55	Damper wire screw
56	Sostenuto tab
57	Damper stop rail
58	Damper wire
59	Damper guide rail
60	Damper head
61	Damper felts
62	String
62A	Understring felt
63	Agraffe
64	Tuning pin
65	Sostenuto rod
66	Sostenuto bracket
67	Key slip
68	End block (Key block, cheek block)
69	Fallboard (Key lid)
69A	Fallboard pivot pin
69B	Fallboard pivot flange
70	Stretcher (Cornice)
70A	Stretcher top
71	Pinblock (Wrest plank)
72	Bellymen felt
73	Plate
73A	Plate strut (Crossbar)
74	Nose bolt nut
75	Plate bolt
76	Plate support dowel
77	Hitch pin
78	Duplex termination



79 Bridge pin
80 Bridge
81 Soundboard
82 Soundboard rib
83–85 Belly rail
(Cross block)
83 Front belly rail
84 Belly rail, spruce
85 Belly rail, birch
86 Lyre support beam
87 Lyre top block
87A Lyre post
87B Lyre box
87C Lyre bottom board
87D Lyre brace
87E Pedal rod guide rail
88 Pedal plate
88A Pedal
88B Pedal rest felt
88C Pedal cup rubber boot
89 Pedal rod
89A Pedal rod nut
90 Trapwork lever
90A Trapwork spring
90B Trapwork leather punching
90C Pitman dowel cushion leather
90D Trapwork lever stop felt
91 Trapwork hook
92 Trapwork block
92A Trapwork pivot pin
92B Trapwork washer
93 Pitman dowel (Trapwork link)
94 Caster
94A Caster socket
95 Leg
95A Leg top

95B Leg-top block
96 Leg plate
96A Leg plate wedge
97 Leg locking cam
98 Leg support block
99 Back bottom
100 Outer rim (Case)
100A Inner rim
101 Beam
102 Lid
102A Lid button
102B Lid hinge
102C Front lid
103 Lid prop rail
103A Lid prop rail felt
103B Lid catch
104 Lock bar
104A Lock bar felt
104B Lock bar buttons
105 Music rack slide
106 Music rack frame
106A Music rack frame stop
107 Music rack (Music desk)
107A Music rack button
107B Music rack hinge
107C Music rack prop hinge
108 Lid prop (Long stick)
108A Short lid prop
108B Lid prop hinge
108C Lid prop button

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Hexagonal Core

Some manufacturers use *hexagonal steel* as the core wire (Figure 83). Its hexagonal shape prevents the copper coil from slipping on it. The advantage of this approach is that you can adjust the length of the winding simply by uncoiling it on either end of the string and cutting it off. The same string, therefore, can be installed in different pianos as a replacement for strings of different lengths but similar diameter. Most supply houses sell such "universal replacement bass strings" in sets of 20 to 30 different sizes. Unfortunately, hex strings don't blend well sound-wise with round-core bass strings. Another disadvantage is that the sharp edges of hexagonal wire cut into agraffes and V bar, making the string "ping" or jump as it's being tuned. In some cases a hexagonal string can't be fine-tuned at all.

Duplex scales

When a string vibrates along its speaking segment, its vibrations, including all of its partials, excite the unmuted segments of strings to vibrate sympathetically. Those segments are:

- **Front duplex**: in grands, the segment between the V bar, agraffe, or a movable fret and the counterbearing; in verticals, the segment between the raised plate flange and the pressure bar[117]
- **Rear duplex**: a segment between the rear bridge pin and a raised termination on the plate (duplex strip, bar, or fret)

All duplex segments in a piano are collectively referred to as *duplex scale* (Figure 86).

Since Theodor Steinway patented it in 1872,[118] duplex scale has been used by most piano manufacturers to enhance tonal brilliance and to increase a piano's perceived loudness. Originally, Steinway pianos were equipped with one fret per unison. Tapping the frets fore-and-aft allowed tuning the rear duplex of each unison individually under full tension. Steinway moved away from this concept and, like most other brands that have a rear duplex, now use termination strips that span entire sections (as seen in Figure 86) and are not intended to be repositioned after the strings are pulled to pitch. Individually tunable rear duplex terminations are found in Mason & Hamlins, old Baldwins, and some other older grands. Fazioli and Petrof allow tuning both the rear and front duplex scales, and have improved their tunability by placing a metal plate under the frets (Figure 87).

Some technicians question the value of the additional effort required to tune the duplex scales because these segments are short and highly inharmonic (see "Inharmonicity" on page 101), and go out of tune much more readily than the speaking segments.

Figure 86 *Front and rear duplex scales.*

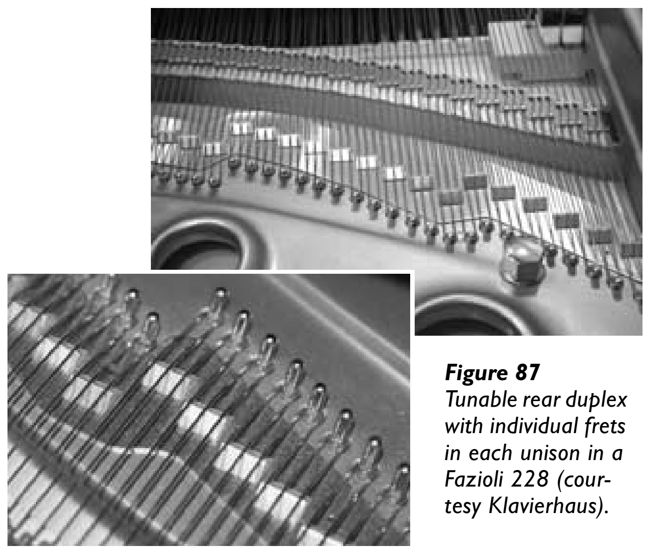

Figure 87 *Tunable rear duplex with individual frets in each unison in a Fazioli 228 (courtesy Klavierhaus).*

Bridges

Modern pianos have two bridges: the *long bridge*, which spans the tenor and treble sections and runs diagonally throughout the soundboard, and the *bass bridge* in the bass section. The bass bridge is higher, making possible the *cross-strung* or *over-strung* design, in which bass strings pass over the strings in the tenor section (Figures 88 and 89). This design is considered to be an improvement over the *straight-strung* design (Figure 90) found in early pianos because it allows the bass strings to be longer, and the bass bridge is closer to the flexible middle of the soundboard. The lowest bass notes sound better in this arrangement.

The bridges transmit vibrations from the strings to the soundboard, but also reflect much of that energy back to the strings, creating a long sustain. Bridges stiffen the soundboard, and that reduces its resonances. (This is discussed in more detail in "Soundboard" on page 43.) Normally, a bridge is about 1½″ [38 mm] wide, and its height is determined by the design of the plate, its thickness, and the amount of downbearing.

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[117] Technically this is not a duplex segment. It is shorter than a typical duplex segment, but vibrates sympathetically and affects tone color.

[118] U.S. patent no. 126,848 (1872).

bridges by bridge pins. These pins are usually made of steel and are brass-plated to reduce the friction between string and pin. Some piano makers, for example Sauter and Ravenscroft, optionally use titanium pins for extra rigidity and hardness. The front and rear bridge pins are arranged so that each string bends slightly around them. They are also angled to keep the strings in firm contact with the bridge even during the strings' upward motion.

Bridge pins are termination points for the speaking length of the string and for the duplex or muted segment behind it (see "Duplex scales" on page 36). To terminate the wire efficiently, these pins must be very rigid—they must reflect the strings' energy, not absorb it. That is why bridge pins are relatively thick.

Traditionally, bridge pins are filed on top after they are installed, but some manufacturers and rebuilders leave them rounded. The filing gives the pins a finished look, and some technicians believe that it improves the clarity of sound. Whether or not this is true, the filing raises a legitimate concern about introducing "false beats" by compressing and scorching the wood by overheating the pins during filing.

Bridge Notching

The top surface of the bridge in front and in back of the bridge pins is notched (cut out) so that the wood will not interfere with the vibrating strings. The notches can be cut with a machine or by hand, as depicted in Figure 107. This is time consuming and requires skill.

The notching must be very precise because, together with the bridge pins, it determines the strings' speaking (and rear duplex) lengths. Whereas the bridge pins terminate the strings' sideways vibrations, the wood of the bridge terminates vertical vibrations. Both terminations must be in the same spot or the string will act as two strings that are slightly out of tune with each other. This causes "false beats." Each notch should start exactly on the line that, in a unison, passes through the center of each bridge pin. With time, however, strings create grooves by denting the bridge (cap), and the effective termination of the wood moves forward from the center-of-the-pins line. That is why the notches should be cut slightly closer to the center of the bridge (Figure 105). The notches should be deep, and form an almost vertical edge at the bridge pins.

Since the speaking segment of all strings in a unison should be equally long, bridge pins are usually installed on a line perpendicular to the strings, and the notching of the bridge cap follows this pattern. However, in some older pianos (for example, Steinway concert and semi-concert grands, models D and C, made from 1884 to the 1930s[123]) the pins may follow the contour of the bridge, especially in the treble. The bridge (cap) is either chiseled parallel to its sides or is notched as depicted in Figure 109. Since the thickness of all strings in a unison is the same

Figure 104 *Notching of a replaced bridge cap.*

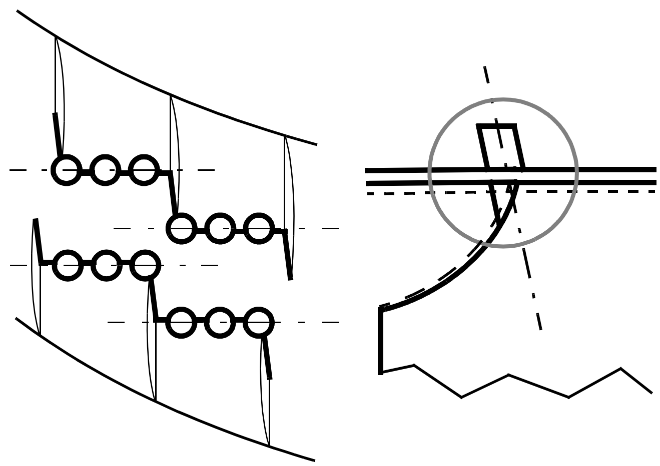

Figure 105 *Bridge notches on a new bridge (cap) should start somewhat closer to the center of the bridge instead of at the exact center of the bridge pins. This compensates for the grooves that form in the bridge cap over time.*

but their speaking lengths vary, each speaking length has a slightly different *inharmonicity* (see page 101). This, in turn, causes the partials of each speaking length to be slightly out of tune with each other. A listener will not notice this, but a tuner will.

Unequal Speaking Lengths

A slight detuning of partials increases sustain through a phenomenon that occurs whenever strings or their partials are *slightly* detuned from a perfect unison. The reason for this is that the strings, which are coupled via the bridge, affect each other as they vibrate. Two strings that are out of tune with each other generate partials that oscillate between vibrating together (in phase) and opposite each other (out of phase). This causes beats. When the partials vibrate only in phase, the energy of the strings is

[123] Bill Shull, "Restorative Conservation in Piano Rebuilding," p. 20.

Figure 106 *Cutting vertical separations between notches (Steinway & Sons factory, New York).*

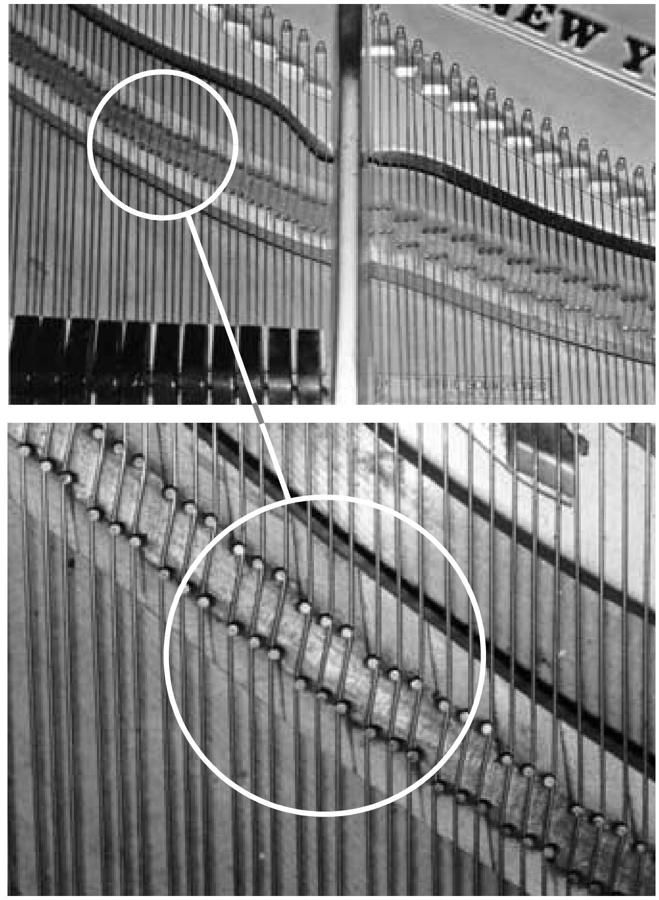

Figure 109 *This style of notching in a ca. 1900 New York Steinway concert grand model D creates unequal speaking lengths of strings in unisons in the mid-treble section. The purpose of unequal speaking lengths is to improve sustain in the "melody" octave.*

Figure 107 *Notching the bridge (Steinway & Sons factory, New York).*

Figure 108 *Bridges are notched sideways at the Fazioli factory.*

transferred more quickly to the soundboard than if they are out of phase part of the time. The reason for this is that the strings, when out of phase, impede the energy transfer of each other, which, in turn, causes them to vibrate longer than if they were always in phase. In effect, encouraging the partials to go out of phase is not unlike increasing the wave impedance of the soundboard and bridge assembly. This is discussed in more detail in "Energy Transfer and Reflection" below.[124]

Unequal speaking lengths are found mostly in the mid-treble ("melody octave"—see page 49), where the volume of sound is inherently weaker than in the rest of the piano. If you plan to replace the bridge cap or the entire bridge, I recommend duplicating the original design.

[124] For a more complete explanation, see Arthur Benade, *Fundamentals of Musical Acoustics*, pp. 335–339.

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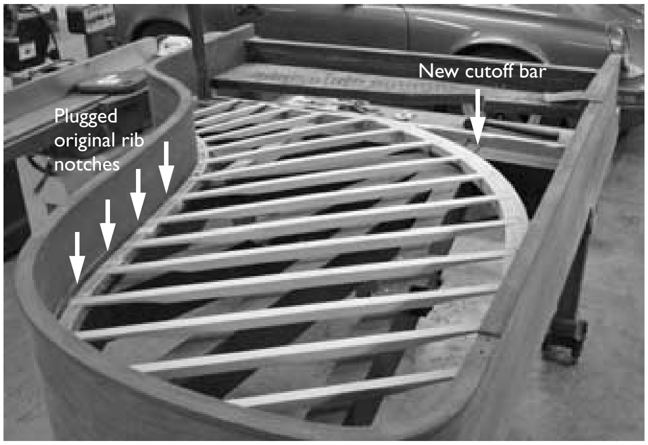

a.

Figure 119 *Thinning the board toward the edges by hand (Fazioli factory).*

b.

Figure 118 *A new cutoff bar is installed in this Steinway B to increase the across-the-grain soundboard stiffness by reducing the lengths of the ribs, and to move the center of the board closer to the long bridge. Note that the original rib notches in the rim were plugged and ribs added to the original design. (Piano redesigned and rebuilt by Erwin's Piano Restoration.)*

c.

Downbearing and Crown

In pianos with bridge pins the soundboard is designed to make the strings press down somewhat on the bridges, creating a *downbearing* force. Assuming that the average angle of deflection at bridges is 1°, a typical average in a new piano, a string stretched at 180 lbs. of force [780 N or 80 kg] exerts a downbearing force of about 3.14 lbs. [14 N or 1.43 kg] (for formulas, see "Measuring String Downbearing" on page 416). Multiplying this by 230 strings in a piano, it becomes clear that the total downbearing force on the soundboard can be 720 lbs. [3,216 N or 328 kg]. At an angle of deflection of 1.5°, the downbearing increases to almost 1,100 lbs. [4,900 N or 500 kg]—the equivalent of six people standing on the soundboard.

Too much downbearing constrains the movement of the soundboard and chokes off the sound. It's like pressing the cone of a loudspeaker—the more you press it, the softer the sound. Without any downbearing, however, the strings would push the bridge and soundboard during the downstroke, but would pull away from them on the upstroke. Despite the angled and staggered bridge pins, this would cause buzzing and rattles, and energy would be lost. Some designers feel that *all* downbearing is detrimental, and use bridge agraffes as an alternative to bridge pins (page 43).

To resist the force of downbearing, the soundboard is crowned toward the strings to make it slightly convex or cylindrical. This also increases the board's stiffness and thus reduces undesirable resonances. In older pianos the loss of downbearing usually is most pronounced in the tenor section where the soundboard is the widest and least stiff, and is accompanied by the loss of crowning.

Manufacturers adjust the downbearing so that it will remain positive (strings bearing down on the soundboard) even after the soundboard loses some of its crowning due to the dessication in drier seasons and a resulting loss of compression. Unfortunately, that means too much downbearing in more humid seasons, which accelerates the long-term loss of crowning and compression. If the soundboard installer could count on the piano being climate controlled, or if the soundboard were impervious to moisture (see Figure 112 on page 45), the amount of downbearing could be much lower and the dynamic range greater. Some manufacturers use bridge agraffes and very little or no downbearing (see "Alternative Bridge Couplings" on page 43) to give their pianos exceptionally long sustain.

In most pianos the downbearing angle should be the greatest in the high treble, up to 1.5°, and should taper to 0.5° in the low tenor and bass. The downbearing of low bass strings is usually too high; this, combined with short backscale (discussed below), chokes off the part of the soundboard that needs to be especially free and flexible. A downbearing of 0.25° is sufficient in that section.

Soundboards are crowned using a *rib crowning* or *compression crowning* technique. Some manufacturers combine the two techniques.

Rib-crowned soundboards (also referred to as "rib-crowned and suspended" or RC&S) have bowed ribs. The shape of the ribs is the main source of the curvature. Before it is glued to the ribs, the board is dried to 5.5 to 6.5% EMC[144] to ensure that it will not crack during periods of low humidity. Higher levels of humidity, to which the board will be later exposed, will cause some compression to build up, but not nearly as much as in a purely compression-crowned board. U.S.-made Baldwin pianos and some Walter pianos used this technique, which is popular among some rebuilders.

Compression-crowned boards are dried to a very low moisture content (4.5 to 5.5% EMC[145]) before they are glued to the ribs, which are either completely flat or slightly bowed (to provide some rib crowning). Moisture, as it reenters the board, increases compression because the ribs prevent the board's underside from expanding. The unrestrained top of the panel expands, making the board bow upward in the middle. The compression is maintained by the ribs, and the rim suspends the assembly.

Compression-crowned boards that have relatively little downbearing, especially in the bass and tenor, tend to produce very long sustain combined with powerful attack, and have a high dynamic ceiling. The soundboard assembly has more "spring" in it and is less restrained in its movement than a rib-crowned assembly. However, compression boards are under greater stress, and will fail if subjected to constant changes or extremes in humidity and temperature. Exposure to high humidity makes the crown increase, but the strings restrain it from above. The swollen wood cells have nowhere to go and become crushed, forming *pressure ridges* in which wood fibers on the surface of the board have been pushed out of their normal position. The crushing of wood cells reduces the compression and lowers the board's stiffness, which lowers the board's wave impedance, increases its resonances, and reduces sustain. After the board is exposed to climate swings year after year, cracks appear, indicating further loss of compression in the board.

Many pianos, however, even some that are over 100 years old, prove that a compression-crowned board kept in reasonably constant climate conditions (page 83) *can* retain enough of its original compression and stiffness to sound good.

In rib-crowned boards the ribs are taller but narrower, and are taller in the middle than on the ends. Some designers shape the ribs as I-beams and make them of stiffer laminated wood. This reduces their range of motion compared to compression boards, but also reduces their susceptibility to failure when exposed to climate extremes.

Backscale

The length of strings between the bridge and a rear termination such as a duplex bar (backscale) can greatly affect the sound, especially in the low tenor and bass. A short, stiff backscale constrains the bridge and soundboard and can choke off the sound of that section, even when the downbearing is acceptable, the bass bridge has an apron, or the soundboard is "floated" in the piano's tail area. This problem can be observed in short grands and verticals where the lowest bass strings may have just one inch [2.5 cm] of length between the rear bridge pins and the hitch pin riser felt. It's better to sacrifice some of the speaking length than to have such a short backscale.

A long backscale, on the other hand, can cause an overly live duplex scale that may need to be partially damped, and can reduce tuning stability. When you "set" a string during a tuning with a hard blow, you are equalizing tensions in the front segments, but less so in the segments behind the bridge. The longer the backscale, the greater the tension inequality between segments.

Melody Octave, Grain Angle, and Reflection of Sound Waves

Most piano music, especially from the romantic era, presents the main melody in the fifth octave—but this is exactly where most pianos lack sustain, especially between F5 and C6. The tenor and upper bass have plenty of volume and sustain, yet one is expected to play the accompaniment in those sections very softly. This is why it is so important for the "melody octave"—or, as some call it, the "killer octave"—to have as much sustain and projection as possible.

As discussed above, sustain is a function of stiffness, and spruce is stiff along its grain. Wherever the bridge runs parallel to the grain of the soundboard is where the stiffness is greatest. Traditionally, modern grands have grain running at an angle of 45°to the belly rail, which tends to be parallel to the fourth-octave section of the long

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144 EMC is "equilibrium moisture content," the amount of moisture that a certain species of wood settles to at a certain temperature and relative humidity (RH). An EMC of 5% in white spruce, for example, corresponds to just under 25% RH at 70°F [21°C]. See R. Bruce Hoadley, *Understanding Wood*, pp. 112–114.

145 W.V. McFerrin gives the figure of 5% in *The Piano: Its Acoustics*, p. 68. Also see Nick Gravagne, RPT, "How Much Crown Should There Be?"

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- **Backchecks** are installed (grands only).
- **Capstan screws** are installed.
- **Key leads** are installed. In quality pianos, additional lead weights may be installed after the action and the keyboard are regulated to finely adjust the touchweight for the particular hammers, action parts, and keys.
- **Keys are installed** on the key frame. The bushings are eased and the keys regulated.

Effects of Touch on Tone

Isn't it fascinating that each pianist can have a unique sound? The piano action doesn't let you control the motion of the hammer after it passes the let off (the point at which the jack escapes under the hammer shank), and it appears that tone can be varied only by changing the acceleration of hammers during their travel toward the strings. Still, a distinctly different tone quality *can* be produced by varying one's touch, even at the same loudness level.

Keyboard noises

Touch affects the tone of the piano because the noises generated by the action, damper mechanism, and keyboard directly affect its overall sound. The noises generated by the keyboard are the most pronounced. As Ramon Alba and Asami T. Inouye suggest,

> the artistic use of this percussiveness [creatively controllable noise generated by the keyboard] is the very secret of virtuosity. This subtle shading 'fills out' the tone color with another dimension—tone 'value'— as in painting when black, white, or greys are added to a basic color to give degrees of 'Value.' What we actually hear are subtle combinations of tone color and shading, allowing gradations of tone color at *each level of intensity*.[162] [italics in original]

Noises generated when the finger strikes the key at rest, and a moment later when the key reaches the bottom, are transmitted through the keys, key frame, key bed, and rim to the soundboard, bridges, and strings. How prominent those noises are can be easily demonstrated: keeping the damper pedal depressed, depress a key, hold it loosely depressed at the bottom of its travel, then pound the key with the other hand. The noise is amplified and sustained for several seconds.

The duplex portions of strings (see "Duplex scales" on page 36), where present, amplify the noises even when the damper pedal is not used.

The amount of time between the noises generated by the key and the hammer striking the strings depends on how loudly one plays the note. A *piano* touch can delay the bottom-of-key-travel noise by as much as 30 ms (0.03 second), whereas a *fortissimo* blow can make it *precede* the hammer strike by almost 10 ms.[163] This has a profound effect on the perception of tone. In soft playing, the key bed noise is a relatively soft part of the sound envelope, whereas loud thumps usurp the sound of the *fortissimo* strikes.

Myth:	**Playing with finger and with a pencil eraser is the same.**
Truth:	Each person has a unique tonal signature that is determined by the strength, shape, weight, and density of his or her fingers, arms, and the entire body. The greatest challenge in reproducing one's playing, and the reason even the best reproducing pianos don't fully convey the subtleties of one's performance, is that their mechanisms don't reproduce the noises and noise-damping effects of a player's touch. For more, see "Effects of Noises on Player and Listener" below.

Action Noises

The noises from the action also play a role in translating the variations of touch into variations in artistic expression. The most variable action noise is that produced by the sliding of hammers on strings during vigorous attacks. The sliding generates a noise (a clank) and affects the vibration of the strings and the prominence of the partials they generate. It introduces complex distortions that give the sound a unique, unpleasant signature.

The sliding of hammers varies, even on impacts of the same force, depending on whether the player hits the key at high speed, or starts slowly and accelerates the attack toward the bottom of key travel. Different rates of acceleration, and their timing during the keystroke, make the action parts flex and twist with the hammer at different distances from the strings. That means that with one type of touch the greatest bending of the hammer shank will occur early in the stroke, whereas with the other it will occur closer to the strings. This has a subtle effect on tone color, as does the subsequent bending and twisting of the hammer head and hammer shank caused by the impact itself. The bending and twisting and, therefore, the sliding at impact depend on the state of the hammer and its shank—a shank that still needs to relax from the belated upward acceleration will produce a sound that is different from a shank that received the greatest acceleration at the beginning of the stroke.

Extra-stiff composite shanks, such as those made by Wessell, Nickel and Gross, reduce hammer sliding and have a cleaner sound during loud playing.

Effects of Noises on Player and Listener

By affecting the sound, the keyboard and action noises, with their spectrum and prominence (see Figure 183c), also affect the **player's perception of touch**. The "crispness" of feel, and how successfully a player interacts with a piano, depend at least as much on the timbre and uniformity of these noises as on the condition of the piano's

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[162] Ramon Alba and Asami T. Inouye, "Piano Tone Color and Touch," p. 36.

[163] Anders Askenfelt and Erik Jansson, "From Touch to String Vibration" in *Five Lectures*.

hammers, action, strings, and overall design. Some piano makers, notably Blüthner and Pleyel, are known for their efforts to suppress these noises, from using double felt punchings to covering the back rail and hammer rest rail with multiple thicknesses of cloth. Instead of paper and cardboard punchings, Blüthner used punchings made of a softer, rag-like material.[164]

The condition of key frame cloths and felts has the most immediate effect on the transmission of keyboard-related noises. Replacing them during rebuilding with high-quality materials restores resilience and gives the action the feel of a "new" piano.

Keyboard and action noises give each pianist a unique **tonal signature**. Several factors are at play: the "pitch" of the noises, their timing and loudness, and the amount of pressure after the strike. Playing "closer to the keys" produces lower-pitched noises and is perceived as deep, sensitive, and rich, while playing "from above" generates higher-pitched noises and is considered brilliant, crisp, and clear, but potentially "choppy" and strident. This perception is reinforced by a slightly greater delay associated with playing closer to the keys—in that case, the sound has a few milliseconds more to develop before the noises affect it. Loud noises can be appropriate when they reinforce the percussive character of music; e.g., in the works of Sergei Prokofiev and Igor Stravinsky, or in jazz. Some pianists produce an almost slapping noise by striking chords from a great height. Finally, the pressure after the strike, although it appears to be a waste of energy, actually damps the noises and makes the sound appear slightly warmer. The difference in the *legato* produced by playing *staccato* with the pedal, and connecting the notes with the fingers, is not merely visual.

Tactile Experience

The pianist's perception of touch also depends on the tactile experience when a finger is in contact with the key. Just as the "transmission chain" passes the noises from the key to the piano belly, it also transmits the vibrations from the belly back to the key, where the player senses them. This can be easily felt in the middle section and the bass. The tactile perception of sound, even though subconscious, is an important factor in a pianist's orientation, expression, and control of touch. In one study, for example, blindfolded pianists were able to identify pianos of different brands with remarkable accuracy, even when "deafened" by white noise.[165]

Electronic pianos illustrate the importance of tactile experience. When the same electronic keyboard controller (the keyboard itself) is attached to a stand with a powerful speaker, pianists report that the action feels more like an actual acoustic piano action. Yamaha even developed their Tactile Response System to simulate the vibrations of an acoustic piano in the keys and pedals of the Avant-Grand, their top electronic piano model (`http://avant-grand.com`).

164 Thanks to Edward Sambell, RPT, for this information.

165 Alexander Galembo, "Perception of Musical Instrument by Performer and Listener."

Piano Action

In its larger sense, the term *action* encompasses all moving parts that make the strings vibrate, or that damp them. These include the keyboard, all action parts, and the damper mechanism (backaction). In grands, *action* is often used to refer to the keyboard and the action frame with its parts, because these slide out of the piano as one unit. In this book, however, *action* is used only for the action frame and all action parts. This assembly is also referred to as the *top stack*.

In grand pianos, the action (top stack) includes:

- Action brackets
- Action rails
- Hammers and hammer shanks
- Wippens
- Let off buttons and screws
- Hammer rest rail (when used)
- Sostenuto monkey and sostenuto rod with brackets (in New York Steinway grands)

In vertical pianos, the action is an assembly above the keyboard that includes:

- Action brackets
- Action rails
- Hammers, hammer shanks, and hammer butts
- Wippens with backchecks and bridle wires
- Dampers and damper levers
- Damper lever rail
- Sostenuto rod or rail (when used)

Types of Grand Actions

In all modern grand pianos the action is of the double-repetition, or "double escapement," type derived from the Herz-Érard design. In the U.S., almost all grand actions dating back to ca. 1870 are of the modern type, while in Germany and Austria the so-called Viennese action was still being made at the beginning of the 20th century (see Figure 12 on page 5). Blüthner pianos from the early 20th century have an action of their own design (see Figure 8 on page 4), while older Pleyel pianos have an awkward implementation of the Herz-Érard action that makes servicing them difficult (see Figure 11 on page 5). All instructions on regulation, repair, and rebuilding in this book are for the modern, double-repetition grand action.

Grand actions vary primarily in:

- Materials (wood vs. composite, wool vs. synthetic bushings, leather vs. synthetic knuckles)
- The profile of rails on which action parts are installed and, correspondingly, the profile of the action parts' flanges that are attached to the rails

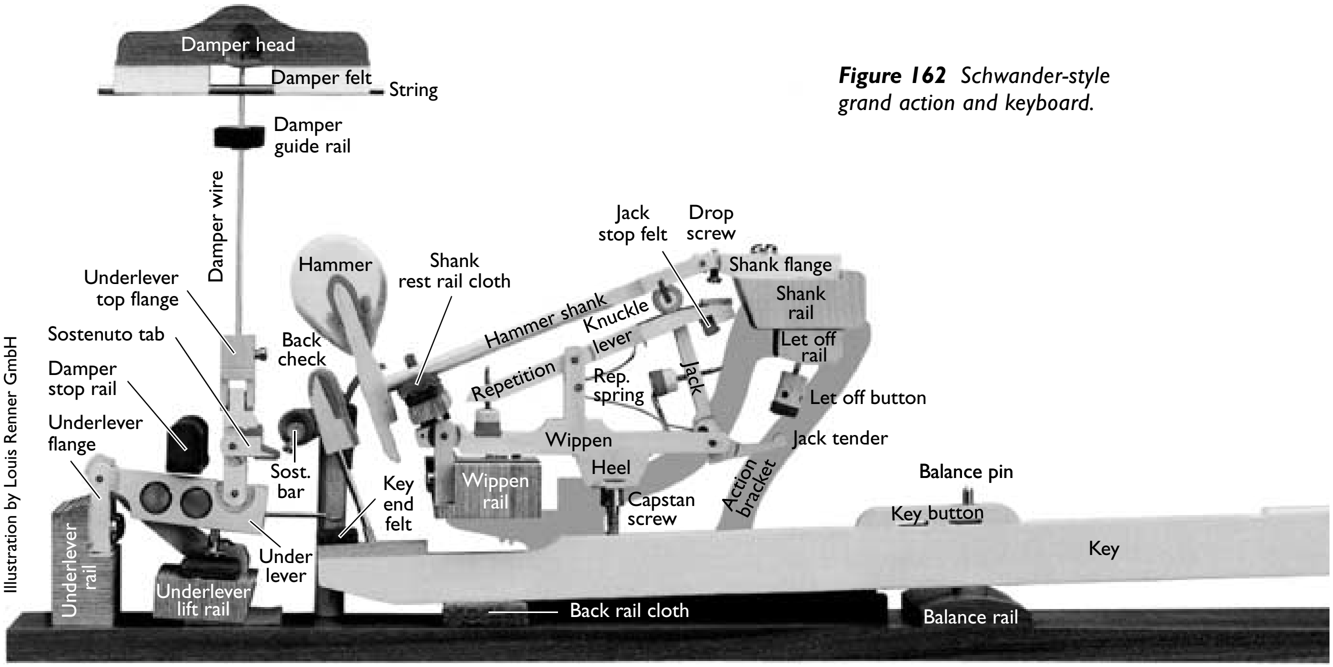

Figure 162 *Schwander-style grand action and keyboard.*

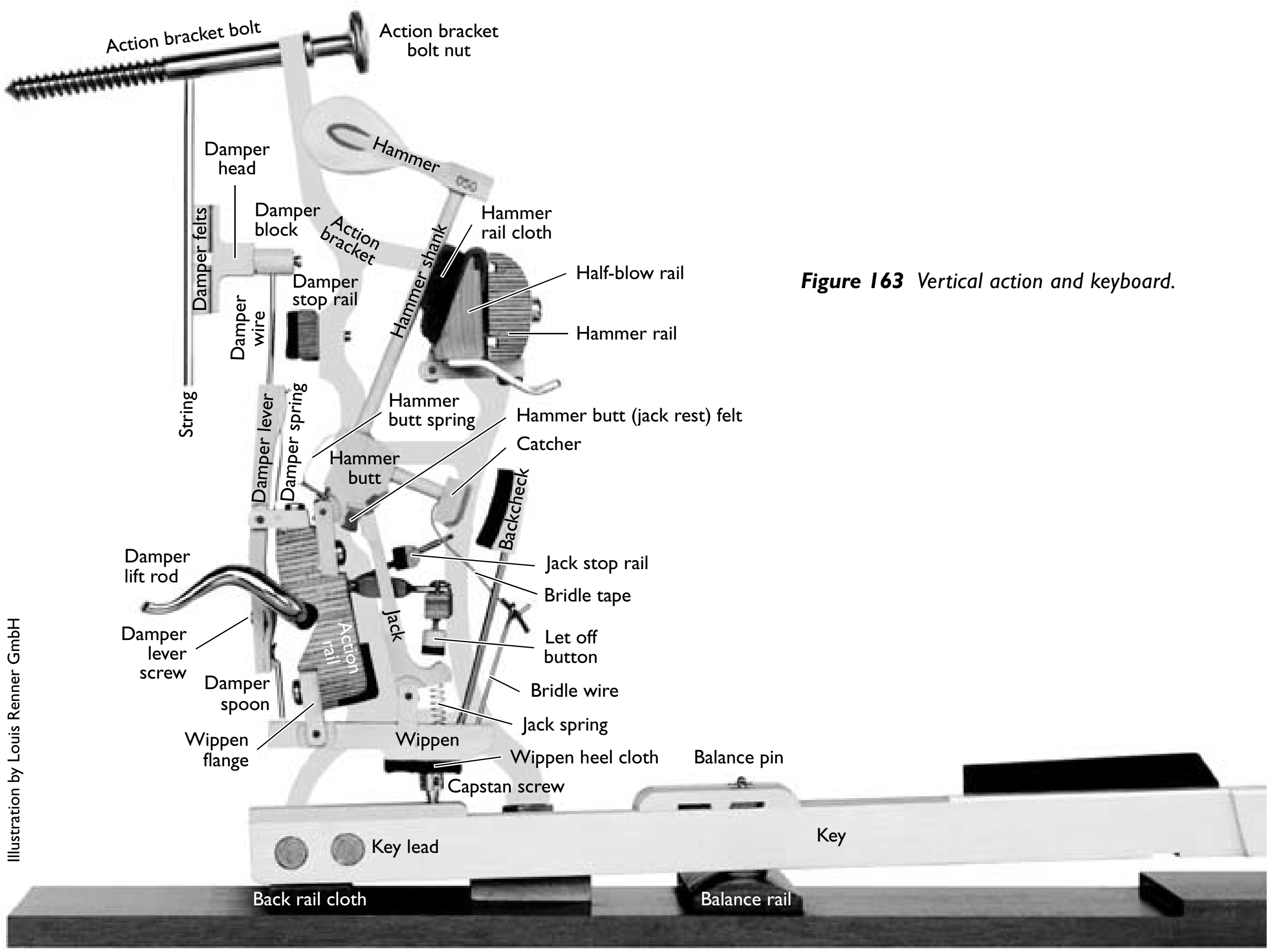

Figure 163 *Vertical action and keyboard.*

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crease or decrease spring tensions, adjusting the effectiveness and resistance of the springs.[175]

Piano Hammers

Piano hammers are made of firm woolen felt that is stretched and glued to a wooden molding. The mass, shape, and density of felt range from heavy, rounded, and relatively soft in the bass, to light, pointed, and dense in the treble. **Mass** determines the loudness of sound and how quickly the hammer rebounds from the strings. The **shape** determines the width of the area of contact between hammers and strings, which affects the timbre (tone quality). **Density** (hardness) affects both the timbre and sound volume. But it is **resilience** that has made felt the irreplaceable material for piano hammers since Jean-Henri Pape's 1826 French patent. The resilience provides the "spring" that allows the hammer to quickly rebound from the strings.

A felt hammer acts as a relatively soft substance during soft blows (similar to a tennis ball), but as a much stiffer substance during hard blows (more like a baseball). This *nonlinear hammer stiffness* produces a *tonal gradient* that gives the piano its expressive range. A note played softly is mellow and has prominent lower partials; played loudly, it is brighter and has a greater proportion of upper partials to the fundamental (Figure 183). This allows the pianist to "bring out" the melody even when it is presented within a thick texture in the tenor or bass range, as is the case in much of the music of Johannes Brahms, for example.

The tonal gradient of piano hammers is made possible by cutting the felt to a triangular shape, then pressing it around a pointed, wooden molding. As a result, the outer layers of felt are under great tension, while the inner layers are increasingly compressed the closer they are to the molding (see Figure 185 on page 72).

For the sound to be clean, focused, and well sustained, hammers must quickly rebound from the strings. For that, the hammers should have high resilience, low mass, and low inertia. Defined as the resistance of mass to acceleration, inertia is particularly detrimental in the treble, where even a slightly prolonged contact between hammer and strings causes a dull, short-decay sound with pronounced impact noise.

Hammer mass must be matched to the stringing scale and belly design (soundboard mass, flexibility, stiffness, and downbearing) to bring out a piano's full potential. If the hammers are too light, the strings and belly may not be sufficiently energized; if they are too heavy, the sound will be loud, distorted, and constrained during loud playing. The demand for mass increases with string length and tension—the heaviest hammers are used in concert grands. Mass decreases more or less evenly from the lowest hammer in the bass to the top treble hammer (see page 285).

[175] Ulrich Sauter, e-mail to author, July 2011.

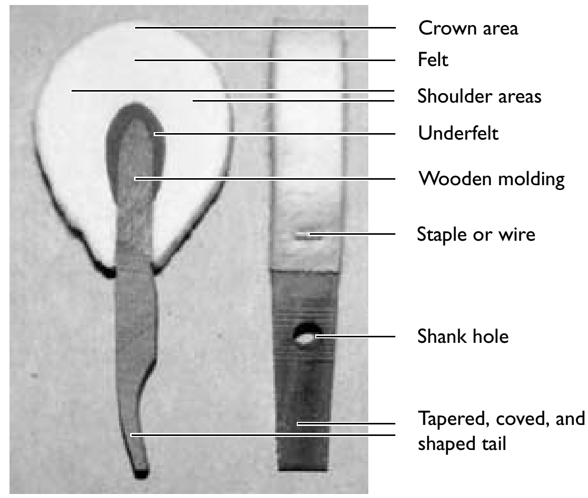

Figure 180 *Piano hammer.*

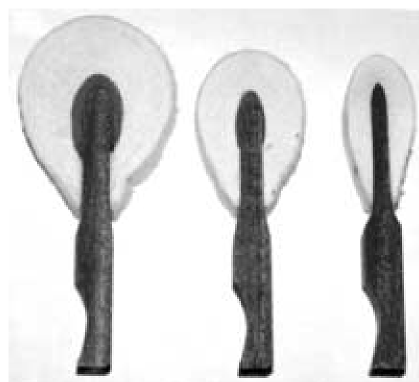

Figure 181 *Hammers with unshaped and untapered tails.*

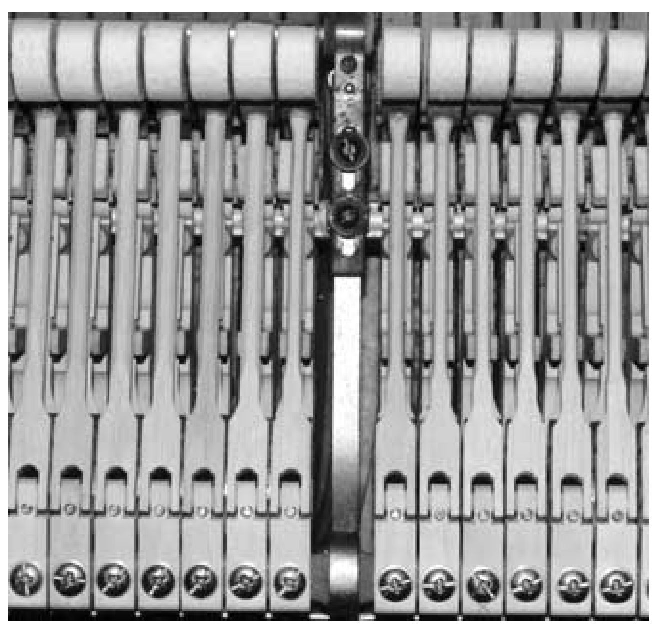

Figure 182 *Treble shanks are thinned to reduce their mass.*

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