Tuning, Timbre, Spectrum, Scale

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With 127 Figures

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Prelude

To seek out new tonalities, new timbres...
To boldly listen to what no one has heard before.

Several years ago I purchased a musical synthesizer with an intriguing feature - each note of the keyboard could be assigned to any desired pitch. This freedom to arbitrarily specify the tuning removed a constraint from my music that I had never noticed or questioned - playing in twelve tone equal temperament[1]. Suddenly, new musical worlds opened and I eagerly explored some of the possibilities: unequal divisions of the octave, n equal divisions, and even some tunings not based on the octave at all.

Curiously, it was much easier to play in some tunings than in others. For instance, 19-tone equal temperament (*19-tet*) with its 19 equal divisions of the octave, is easy. Almost any kind of sampled or synthesized instrument plays well: piano sounds, horn samples, and synthesized flutes all mesh and flow. 16-tet is harder, but still quite feasible. I had to audition hundreds of sounds, but finally found a few good sounds for my 16-tet chords. In 10-tet, though, none of the tones in the synthesizers seemed right on sustained harmonic passages. It was hard to find pairs of notes that sounded reasonable together, and triads were nearly impossible. Everything appeared somewhat out-of-tune, even though the tuning was precisely ten tones per octave. Somehow the timbre, or tone quality of the sounds seemed to be interfering.

The more I experimented with alternative tunings, the more it appeared that certain kinds of scales sound good with some timbres and not with others. Certain kinds of timbres sound good in some scales and not in others. This raised a host of questions: What is the relationship between the timbre of a sound and the intervals, scale, or tuning in which the sound appears "in tune"? Can this relationship be expressed in precise terms? Is there an underlying pattern?

This book answers these questions by drawing on recent results in psychoacoustics, which allow the relationship between timbre and tuning to be

[1] This is the way modern pianos are tuned. The seven white keys form the major scale and the five black keys fill in the missing tones so that the perceived distance between adjacent notes is (roughly) equal.

explored in a clear and unambiguous way. Think of these answers as a model of musical perception that makes predictions about what you hear: about what kinds of timbres are appropriate in a given musical context, and what kind of musical context is suitable for a given timbre.

Tuning, Timbre, Spectrum, Scale begins by explaining the relevant terms from the psychoacoustic literature. For instance, the perception of "timbre" is closely related to (but also quite distinct from) the physical notion of the *spectrum* of a sound. Similarly, the perception of "in-tuneness" parallels the measurable idea of *sensory consonance*. The key idea is that consonance and dissonance are not inherent qualities of intervals, but are dependent on the spectrum, timbre, or tonal quality of the sound. To demonstrate this, the first audio track on the accompanying CD plays an example where the octave has been made dissonant by devious choice of timbre, even though other, non-octave intervals remain consonant. In fact, almost any interval can be made dissonant or consonant by proper sculpting of the timbre.

Dissonance curves provide a straightforward way to predict the most consonant intervals for a given sound, and the set of most-consonant intervals defines a scale *related* to the specified spectrum. These allow musicians and composers to design sounds according to the needs of their music, rather than having to create music around the sounds of a few common instruments. The spectrum/scale relationship provides a map for the exploration of nonharmonic musical worlds.

To the extent that the spectrum/scale connection is based on properties of the human auditory system, it is relevant to other musical cultures. Two important independent musical traditions are the gamelan ensembles of Indonesia (known for their metallophones and unusual five and seven note scales) and the percussion orchestras of classical Thai music (known for their xylophone-like idiophones and seven tone equal tempered scale). In the same way that instrumental sounds with harmonic partials (for instance, those caused by vibrating strings and air columns) are closely related to the scales of the West, so the scales of the gamelans are related to the spectrum, or tonal quality, of the instruments used in the gamelan. Similarly, the unusual scales of Thai classical music are related to the spectrum of the xylophone-like *renat*.

But there's more. The ability to measure sensory consonance in a reliable and perceptually relevant manner has several implications for the design of audio signal processing devices and for musical theory and analysis. Perhaps the most exciting of these is a new method of *adaptive tuning* that can automatically adjust the tuning of a piece based on the timbral character of the music so as to minimize dissonance. Of course, one might cunningly seek to maximize dissonance; the point is that the composer or performer can now directly control this perceptually relevant parameter.

The first several chapters present the key ideas in a nonmathematical way. The later chapters deal with the nitty-gritty issues of sound generation and manipulation, and the text becomes denser. For readers without the background to read these sections, I would counsel the pragmatic approach of skipping the details and focusing on the text and illustrations.

Fortunately, given current synthesizer technology, it is not necessary to rely only on exposition and mathematical analysis. You can actually listen to the sounds and the tunings, and verify for yourself that the predictions of the model correspond to what you hear. This is the purpose of the accompanying audio CD. Some tracks contain simple examples that help your ear focus on the appropriate aspects of a sound to understand the psychoacoustic definitions and terms. Other tracks contain musical compositions. Some fulfill the predictions of the model, and some violate them; it is not hard to tell the difference. The effects are not subtle.

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This book owes a lot to many people.

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The very greatest thanks go to *Ann Bell* and the *Bunisattva*.

Variables, Abbreviations, Definitions

a_i	Amplitudes of partials.
attack	The beginning portion of a signal.
cent	An octave is divided into 1200 equal sounding parts called cents. See Appendix B.
-cet	Abbreviation for cent-equal-temperament. In n-cet there are n cents between each scale step, thus 12-tet is the same as 100-cet.
CDC	Consonance-Dissonance Concept, see [Tenney 1988].
$d(f_i, f_j, a_i, a_j)$	Dissonance between the partials at frequencies f_i and f_j with corresponding amplitudes a_i and a_j.
D:	Indicates a sound recording in a bibliographic entry .
DFT	Discrete Fourier Transform. The DFT of a waveform (sound) shows how the sound can be decomposed into and rebuilt from sine wave partials.
D_F	Intrinsic dissonance of the spectrum F.
$D_F(c)$	Dissonance of the spectrum F at the interval c.
envelope	Evolution of the amplitude of a sound over time.
F	Name of a spectrum with partials at frequencies $f_1, f_2, ..., f_n$ and amplitudes $a_1, a_2, ..., a_n$.
f_i	Frequencies of partials.
fifth	A 700 cent interval in 12-tet, or a 3:2 ratio in JI.
FFT	Fast Fourier Transform, a clever implementation of the DFT.
FM	Frequency Modulation, when the frequency of a sine wave is changed sinusoidally.
formant	Resonances which may be thought of as fixed filters through which a variable excitation is passed.
GA	Genetic Algorithm, an optimization technique.
harmonic	Harmonic sounds have a fundamental frequency f and partials at integer multiples of f.
Hz	Hertz is a measure of frequency in cycles per second.
JI	Just Intonation, the theory of musical intervals and scales based on small integer ratios.
JND	Just Noticeable Difference, smallest change that a listener can detect.

K	K means $2^{10} = 1024$. For example, a 16K FFT contains 16*1024=16384 samples.
m	Number of steps (intervals) in a scale.
MIDI	Musical Interface for Digital Instruments, a communications protocol for electronic musical devices.
n	Number of partials in a spectrum.
octave	Musical interval defined by the ratio 2:1
partial	The partials (overtones) of a sound are the prominent sine wave components in the DFT representation.
periodic	A function, signal, or waveform $w(x)$ is periodic with period p if $w(x+p) = w(x)$ for all x.
r and s	Ratios between scale steps or between partials.
RIW	Resampling with Identity Window, a technique for spectral mapping.
semitone	In 12-tet, an interval of 100 cents.
signal	When a sound is converted into digital form in a computer it is called a signal.
sine wave	The "simplest" waveform is completely characterized by frequency, amplitude, and phase.
SMF	Standard MIDI File, a way of storing and exchanging MIDI data between computer platforms.
spectral mapping	Technique for manipulating the partials of a sound.
steady state	The part of a sound that can be closely approximated by a periodic waveform.
-tet	Abbreviation for tone-equal-tempered. 12-tet is the standard Western keyboard tuning.
transient	That portion of a sound that cannot be closely approximated by a periodic signal.
waveform	Synonym for signal.
whole tone	In 12-tet, an interval of 200 cents.
xenharmonic	Strange musical "harmonies" not possible in 12-tet.
xentonal	Music played with related timbres and scales.
$\oplus$	Pronounced *oh-plus*, this symbol indicates the "sum" of two intervals in the symbolic method of constructing spectra.