UNIV 213 Science & Engineering of Music & Sound Spring 2020

Review Sheet for Final Exam
(incorporates modifications to accommodate remote instruction)

Please review the revised exam policies that will be sent to you via e-mail that will address the remote administration of the Final Exam. The “Exam Policies” section of the Exams page at the course web site will also be revised to reflect the updated policies.

The following is a list of topics that could appear in one form or another on the exam. Not all of these topics will be covered, and it is possible that an exam problem could cover a detail not specifically listed here. However, this list has been made as comprehensive as possible. You should be familiar with the topics on the review sheet for the previous exam as well.

Although significant effort has been made to ensure that there are no errors in this review sheet, some might nevertheless appear. The textbook is the final authority in all factual matters, unless errors have been specifically identified there either by the authors (in the form of published errata) or by me. You are ultimately responsible for obtaining accurate and authoritative information when preparing for your exam.

Combination Tones and Harmony (Chap. 8) – see solutions to HW #3 for more details

- beats between tones that are close in frequency (a linear effect)
- difference tones (a nonlinear effect) produced by two tones at frequencies f_1 and f_2
  - primarily an effect of the human auditory system; that is, they are mostly not produced by musical instruments (although they can be in some cases)
  - quadratic (2^{nd}-order) tones: $|f_1 - f_2|$
  - cubic (3^{rd}-order) tones: $|2f_1 - f_2|$ and $|f_1 - 2f_2|$
  - higher-order (4^{th}, 5^{th}, 6^{th}, etc.) tones can also be generated but loudness usually drops quickly with increasing order
- consonance and dissonance
  - consonance is the subjective sense of “harmoniousness;” dissonance is the subjective sense of two tones “fighting” each other and possibly producing a almost buzzing-like sound; dissonance is not necessarily bad – the psychological tension it produces in music can evoke darker emotional responses that are vital in artistic expression
  - importance of Figs. 5.10 and 8.15 in the textbook
  - critical bandwidth of the ear plays a vital role in determining level of consonance
  - some musical intervals are more consonant than others, primarily because of the differences in frequency of their partials (harmonics); however, very low frequency intervals can be very dissonant if the differences in their fundamental frequencies is a small fraction of the critical bandwidth
  - triads (chords) can sound somewhat or very dissonant if the intervals they contain are dissonant; moreover, slight mistunings (possibly due to use of equal temperament) can cause beating

- beats of mistuned consonances
  - beating between two tones that have a frequency ratio that is not a perfect integer ratio; fundamental relationship:

    $$f_2 = \frac{n}{m} f_1 + \delta$$

    where n and m are integers that express the frequency ratio required for a perfect interval (e.g., $n/m = 3/2$ for a perfect fifth), and δ is the error frequency
  - error frequency δ is the difference between the upper frequency of the perfect interval and the actual value of f_2
  - if f_1 and f_2 do not form a perfect interval reducible to a ratio of integers, then a listener will hear beating at the frequency $m\delta$, where m is the same integer that appears in the formula above
  - error frequency and beat frequency (rearrangement of expression for f_2 above):

    $$\delta = f_2 - \frac{n}{m} f_1 \quad \rightarrow \quad m\delta = mf_2 - nf_1$$

    if negative value of δ is obtained, it just indicates that the actual upper frequency f_2 is below what it should be for a perfect interval; the number of beats per second heard (equal to $m\delta$) is the same whether δ is positive or negative

Musical Scales and Temperament (Chap. 9) – see solutions to HW #3 for more details

- Pythagorean scale
  - originated in 500s BCE by Pythagoras and his followers
  - based on circle of fifths (and fourths)
  - raising a tone by a perfect fifth is the same as lowering it by a perfect fourth after adjusting for the change in octaves
  - major disadvantages are mistuning of thirds and progressive mistuning that occurs after successively raising by fifths; e.g., raising a note by fifths 12 times should produce the same note seven octaves higher, but

    $\left(\frac{3}{2}\right)^{12} f_{\text{start}} \neq 2^7 f_{\text{start}}$ (It's close, though.)
- just intonation scale
  - corrects many flaws in the Pythagorean system
  - most (but not all) major and minor thirds have the correct frequency ratios
  - the I, IV, and V triads (major chords) have perfect 4:5:6 frequency ratios
  - major disadvantages are that transposition (changing from one scale to a different scale for the same piece of music) causes noticeable mistunings of all of the intervals in the new scale; requires retuning of the instruments to change scales, which is very difficult for some instruments, such as pianos and organs
- western chromatic scales contain all 12 notes in an octave, including all sharps and flats; e.g., the C chromatic scale is:

  C C♯ D D♯ E F F♯ G G♯ A A♯ B C
  - semitone = interval between each note in the chromatic scale
  - whole step = two semitones
  - half step = one semitone
- equally tempered scale
  - represents a compromise; most of the important intervals are not perfect, but all of them are close enough not to be objectionable to most listeners
  - based on the semitone (smallest) interval having a frequency ratio of $2^{1/12}$

- mathematical basis: the frequency ratio corresponding to the semitone is the same for all 11 intervals (between the 12 notes) in the chromatic scale; if f_{start} is the frequency of the first note of a scale and r_s is the frequency ratio corresponding to one semitone:

  $$(r_s)^{12} f_{\text{start}} = 2 f_{\text{start}} \quad \rightarrow \quad (r_s)^{12} = 2 \quad \rightarrow \quad r_s = 2^{1/12}$$

- major advantage is that the frequency of any note can be found by counting octaves and semitones from the standard frequency of A_4 (440 Hz) and then multiplying the appropriate number of times by 2 or 1/2 (for octaves) and $2^{1/12}$ or $2^{-1/12}$ (for semitones)

String Instruments (Chap. 10)

- tuning of strings in violin, viola, cello, and bass
- tuning of strings in guitar
- resonant frequency of a vibrating string (see Sec. 4.3 of textbook)

  $$f_n = \frac{n}{2L}\sqrt{\frac{T}{\mu}} ,$$

  where n = index of harmonic frequency (fundamental corresponds to n = 1), L = length of string between fixed ends (m, meters); T = tension on string (N, newtons), μ = mass per unit length (kg/m, kilograms per meter)
- vibration due to plucking strings
  - initial shape of string (before pluck is released) is triangular
  - at end of pluck (at the instant of release), peak of triangle splits into two peaks that propagate in opposite directions along the string
  - propagating peaks are reflected at the fixed ends of the string; the reflected peaks point in opposite direction of incident peak (e.g., if incident peak was up, reflected peak will be down); sometimes called “inversion” or “180° phase shift”
  - sound spectrum (relative strengths of harmonics) depends on where string is plucked; plucking at specific locations suppresses specific harmonics
- vibration due to bowing strings
  - as with plucking, the shape of a bowed string is essentially triangular, but only one peak propagates up and down the string instead of two counterpropagating peaks
  - bowing is characterized by alternating periods of sticking and slipping between bow and string
  - during sticking, the part of the string touching the bow moves with the bow because of friction
  - during slipping, the string moves in the opposite direction of the bow; the restoring force of the string points in the opposite direction of the bow’s motion; the force is strong enough to overcome friction and slide the string along the bow
  - transitions between sticking and slipping occur as the peak of the propagating triangle passes through the bowing location
  - as with plucking, the fundamental vibration frequency of a bowed string is determined by the length, tension, and mass per unit length, not the location of the bow along the string
  - just like plucking, bowing generates harmonics in addition to the fundamental frequency, but the relative strengths of the harmonics are different; thus, bowing results in a different timbre than plucking
  - loudness of bowed string is determined primarily by the bow speed and the location of the bow relative to the bridge, not by bowing force

- most of the sound from an acoustic string instrument (e.g., violin, classical guitar) comes from the body, not from the strings, and usually from the top plate; the vibrations of the strings transfer to the body through the bridge; the body then radiates most of the sound
- body of a string instrument has many vibration modes; they can be revealed by observing Chladni patterns
- movement of air in and out of the hole(s) in the instrument's body enhances the low-frequency spectrum via the Helmholtz cavity resonances (resonant frequencies of an enclosed space)
- cross-bracing on a guitar's top plate affects its resonant frequencies
- sound from an electric guitar is mainly obtained via the pick-ups located under the strings; the body resonances are far less important; in fact, many electric guitars do not have hollow bodies; two or three pick-ups are used to sample all of the vibration modes of the strings because one pick-up location might be a vibration node or "dead spot"
- electric bass guitar has only four strings tuned to E_1, A_1, D_2, and G_2; it has a longer fretboard than a standard electric guitar
- guitar strings are often made a little long to compensate for the increased tension caused by the guitar frets when a string is pressed down to the fretboard

Brass Instruments (Chap. 11)

- resonant frequency of a closed cylindrical pipe (see Sec. 4.5 of textbook)

  $$f_n = n\frac{v}{4L},$$

  where n = index of harmonic frequency (fundamental corresponds to n = 1) and the indices are odd integers, L = effective length of pipe (in meters); v = speed of sound at the ambient temperature (in meters per second)
- acoustic impedance is a measure of the ability of a medium to allow sound to pass through it; it is defined as the ratio of the pressure at some location to the volume flow rate of the medium (usually air in the case of musical instruments) at the same location; for example, for given pressure level, a medium with a high acoustic impedance will not allow the air particles to flow very easily whereas the air particles in a medium with a low acoustic impedance flow much more easily
- the acoustic impedance within a pipe driven by sound waves at one end varies along the length of the pipe because of the reflected waves from the opposite end; the combination of the incident and reflected waves cause variations in compressed and rarefied air related to the standing wave pattern within the pipe
- a brass instrument player "buzzes" their lips (forces them to vibrate) inside the mouthpiece, which causes puffs of air to be released into the instrument at a very high rate (hundreds of puffs per second); the puffs of air create pressure waves, which are reflected at the opposite end (the bell); the reflected waves interact with the player's vibrating lips, causing the frequency of the vibration to match the timing of the reflected waves; the result is that the vibration of the lips is supported by the instrument at a specific frequency and its harmonics
- most of the sound energy is contained within the instrument; only a small fraction of the sound energy is released through the bell within a given interval of time because most of the sound energy arriving from the mouthpiece is reflected back toward it; the sound pressure level within a brass instrument would be ear-splitting if a person could experience it

- flared bell of brass instruments
  - changes the frequency and height of the acoustic impedance peaks; the effective length of the instrument increases with frequency because of the bell
  - changes the directionality of the sound from the instrument; high frequencies are loudest in the direction the bell is pointing
  - changes the spectrum of the radiated sound
  - allows more efficient radiation of the sound
- operation of valves and slides and how they affect sound spectrum
- special cases of French horn (hand in bell and two lengths of pipe)
- spectra and effects of the bell and loudness
- mutes and their effects

Woodwind Instruments (Chap. 12)

- resonant frequency of a closed cylindrical pipe (see Sec. 4.5 of textbook)

  $$f_n = n\frac{v}{4L},$$

  where n = index of harmonic frequency (fundamental corresponds to n = 1) and the indices are odd integers, L = effective length of tube (in meters); v = speed of sound at the ambient temperature (in meters per second)
- vibrating reed releases puffs of air into the instrument's cylindrical body; the vibration frequency is determined by the resonances of the vibrating air inside the body; the reflected pressure waves reinforce the vibrations of the reed in a manner similar to the way the vibration of the lips of a brass player are reinforced
- tone holes change the effective length (also called the acoustical length) of the tube; the amount of the change depends on the diameter of the holes and length of the holes (i.e., the thickness of the tube plus the length of any collar that might be fitted on the tube at the hole); see Fig. 12.5 in the textbook for details
- a series of regularly spaced tone holes introduces a cut-off frequency above which sound easily propagates but below which sound reflects; results in high peaks in the acoustic impedance curve below the cut-off frequency and low or ill-defined peaks above
- cylindrical vs. conical bores (i.e., constant vs. increasing diameter of the tube) and effect on mode frequencies; cylindrical bores mostly exhibit only odd harmonics, while conical bores include the even harmonics as well as odd; quantity of higher harmonics drops off the larger the conical bore angle
- clarinets play in three registers, which are related to resonant frequencies of the tube; the three registers are associated with the fundamental, third, and fifth harmonic frequencies
- the second register of a clarinet is a twelfth interval higher than the first because the second register uses the third harmonic of the fundamental resonant frequency; raising a pitch by a twelfth is the same as raising it by an octave (×2) followed by a fifth (×3/2); the combination is ×2×3/2 = ×3, the third harmonic
- register holes are used to emphasize a specific register during playing; their purpose is to "spoil" the resonance(s) below the one for the desired register
- double reed instruments (e.g., oboe, bassoon, saxophone) have conical tubes and rich harmonic content, including even harmonics
- flutes and piccolos use "air reeds," which involves flow control rather than pressure control from the player; flute resonances are those of a cylindrical pipe open at both ends, so all of the harmonics of the fundamental are present; registers are changed by controlling blowing pressure and the position and shape of the lips

Percussion Instruments (Chap. 13)

- bars (e.g., glockenspiel, marimba, xylophone, vibraphone)
  - frequency of transverse vibrations of uniform rectangular bar:

    $$f_n = \frac{\pi v_L K}{8L^2} m^2,$$

    where n = mode number (fundamental corresponds to n = 1), L = length of bar (meters); v_L = speed of sound in the bar (much higher than in air); K = radius of gyration, m = 3.0112, 5, 7, 9, (2n + 1)
  - first few transverse modes of vibration have ratios 1.00 : 2.76 : 5.40 : 8.90
  - bars of marimbas, xylophones, and vibraphones are deeply arched to alter the ratios of the overtone frequencies; the first one or two overtones are harmonically related (or nearly so) to the fundamental
  - material type and weight of mallets used to play barred percussion instruments affect the timbre
- membranes (drums)
  - resonant frequency of an ideal vibrating membrane with the outside edge of the membrane fixed (immovable):

    $$f_{mn} = \frac{1}{2a}\sqrt{\frac{T}{\sigma}}\beta_{mn},$$

    where a = radius of membrane (m, meters), T = surface tension of membrane (N/m, newtons per meter), σ = mass per unit area (kg/m^2, kilograms per square meter), and β_{mn} = zeroes of Bessel function
  - because the β_{mn} values are not equivalent to ratios of integers, the sound from a vibrating membrane does not contain harmonically related overtones; it is therefore difficult to identify a pitch
  - air loading in drums with a solid enclosure (e.g., timpani) changes the pitches of the overtones significantly and can produce some harmonically related overtones
  - drums with two flexible membranes (heads), such as snare drums and tomtoms, have indefinite pitches and can therefore blend with music written in any key (scale); the two heads are usually set to different tensions
- **not covered on Final Exam**: vibrations of plates (e.g., cymbals, gongs, and steelpans) and bells (Sections 13.12 through 13.18)

Keyboard Instruments (Chap. 14)

- piano
  - playing range of over seven octaves
  - strings are hammered when key is played
  - soundboard radiates most of the sound energy
  - most notes have three strings; their tuning relative to each other affects decay rate and timbre
  - loudness is easily controlled by the force applied by the player on the key
- harpsichord
  - popular in the Baroque period
  - strings are plucked (by a plectrum attached to the key) rather than struck
  - strings are under much less tension (about 1/10) than in a piano
  - loudness is controlled by stops
- pipe organ

Auditorium Acoustics (Chap. 23) – **not covered on Final Exam**

Electronic Reinforcement of Sound (Chap. 24) – **not covered on Final Exam**

Relevant course material:

HW:	#3
Readings:	Assignments from Feb. 17 through end of semester
Web Links:	Wave Interference and Beat Frequency
	Amplitude Modulation
	Pitch Frequencies in Equal-Tempered Scale