Birding by Ear, Visually

Part 1: Birding Acoustics

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aba.org/birding/v42n4p63w1.html

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Most birders cannot live without bird sound. Aural identification increases efficiency more than any other skill. If all sounds were equally incomprehensible to you, you would have to visually identify every robin and towhee to find the visiting Varied Thrush. Anyone who has traveled abroad knows, or once knew, this problem. Moreover, some birds, such as most owls and nightjars and some rails, are unlikely to be detected visually because they are active mainly at night. And then there are the species that are easy to see, but still difficult to identify visually—for example, *Chaetura* swifts, *Catharus* thrushes, wood-pewees, and empids. I'm much more comfortable with these aurally than visually. Beyond the identification quest is the sheer joy (Kroodsma 2005, 2009) of hearing bird sounds in all their kinds, melodious and noisy, serene and hyperactive; of knowing the sounds themselves as well as who made them.

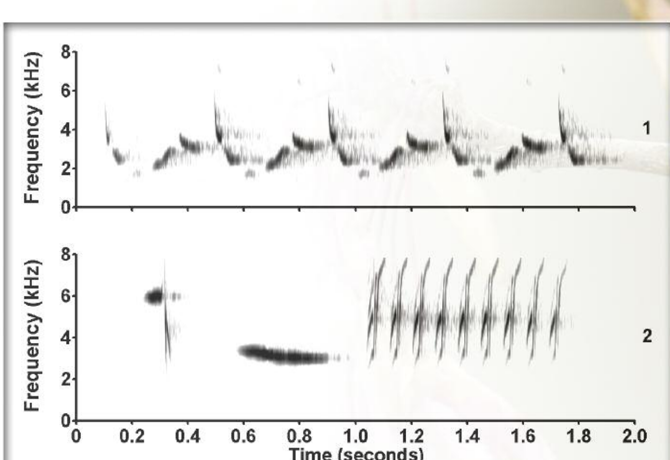
The crack birders know almost all species by their sounds. For most of us, though, aural skills lag behind visual ones. So why not visualize sound as well as shape and color? We can do this by recording the sounds in the field and using a computer to convert the digitized sound waves to sound pictures (Kroodsma 2009, Strycker 2009), via audio spectrograms (also known as "sonograms") and oscillograms (graphs of the waveform of the sound). These visual representations of sounds help us (1) name different kinds of sounds for clearer communication (Pieplow 2007), (2) increase "ear-birding" skill by engaging visual memory in building a library of known sounds, and (3) objectively evaluate recordings that are presented as documentation for distributional records.

With improvements in technology and the emergence of a creative commons on the internet (for example, xeno-canto.org and earbirding.com), not to mention free access to traditional archives (for example, tinyurl.com/djfxxe and tinyurl.com/24svbaq), recordings and sound pictures will play an increasingly important role in ear birding. Lest anyone miss out on the fun, I present here visual primers on the two foundations of ear birding: acoustics (this article) and syntax (later this year in *Birding*).

The basic unit of bird sound is the *note*, which, just like a musical note, is a sound that is continuous in time. My goal in this article is to show how different classes of notes look and to outline the different ways birds produce similar-looking notes. I'll also show how small, easy modifications can produce big effects, which can be diagnostic. In a companion article, to appear later this year in *Birding*, I'll look at the rules birds use to combine notes into *phrases*, phrases into *songs* (Fig. 1), and songs into singing performances (Fig. 2). Such rules produce the broader temporal patterns of vocalizing that we depend upon for identification of most singing birds.

In an article in *Birding* in 2007, Nathan Pieplow introduced a spectrographically based vocabulary for describing how sounds sound. I aim to complement his important work by shifting the focus from your brain to the bird's vocal tract, with a nod to the brains of the intended receivers of these sounds. I believe you will be astonished at the variety of sounds birds make and at the variety of techniques they use to make them. No other natural soundmakers come anywhere close to the virtuosity of birds, and

Fig.1. Birds' *songs* are composed of *phrases*, which are composed of *notes*. Shown are single songs of a **Carolina Wren** from Warren County, Virginia, 9 April 1983 (top) and an **Eastern Towhee** from Hayward County, North Carolina, 26 July 2006 (bottom). Each continuous trace is a note. Carolina Wren songs are tandem repeats of a single phrase-type, each of which is a permanent member of the bird's repertoire of two or three dozen. This phrase-type contains five notes. The fifth phrase in the song is incomplete. The towhee's song proceeds according to a plan that has been immortalized as *drink your tea!* A brief whistle and sharp click provide the *drink*, a low whistle is the *your*, and *tea* is a slow trill. Each element in the trill is actually a two-note phrase.



Carolina Wren.
Harris County, Texas; December 2008. Photo by © Alan Murphy.

you deserve, as a birder, to know just how good they are. Be amazed, but not dismayed, by all the variety. Every sound is an event in time, and almost all sounds have a simple and discernible pitch trend, a tune that you could whistle. The variety comes from what birds do with *carrier frequencies*.

Carrier Frequencies

The underlying sound, or carrier frequency, is a simple, thin, line on a sonogram. We can characterize this line as a *whistle* if it is flat, a *click* if it is nearly vertical, and a *slur* or *warble* if it is in between. These names just describe points on a continuum, but they can be useful.

Many bird sounds, though, are not so simple, because the bird adds information to the simple pitch trend of the carrier. This process of "modulation" gives us derived spectrographic shapes that I refer to as *buzzes*, *trills*, and *chords*.

A whistle is flat on a sonogram (Fig. 3), which means it does not change frequency. The everyday term for frequency is "pitch." The latter is actually a perceptual term, whereas the former is a physical quantity, the number of oscillations per second of the sound source. The inset in Fig. 3 is a short segment of the oscillogram, which graphs the waveform of the sound. Notice that it is a simple sine wave—from trigonometry, remember? The oscillations above and below zero are a reading of the back-and-forth movements of a diaphragm in a microphone, which mimics the movements of membranes in the vocal organ, or syrinx, of the bird. The oscillations of the membranes initiate pressure waves, which are "read" by the microphone. There's not room for the oscillogram of the entire sound, above the sonogram, to show that level of detail, but it does show (in volts) the time-varying amplitude (loudness) of the sound. The frequency of 4,000 oscillations (or cy-

Fig.2. Shown here are five songs from a *bout* of singing by an **American Robin** from Wasco County, Oregon, 9 April 2004. Each song is a slightly different combination of the bird's finite repertoire of phrase-types, six of which are indicated by letters. Each phrase is composed of one or more notes. The unlettered phrases are the fainter *hissely* phrases discussed by Kroodsma (2005:30). They are not used by the tanagers and grosbeaks whose songs may be confused with those of robins.

American Robin. *Lane County, Oregon; June 2009. Photo by © Joe Fuhrman.*

cles) per second is referred to as 4,000 Hertz (Hz), or 4 kiloHertz (kHz). It translates to a flat line at 4 kHz on the vertical axis of the sonogram, which, as you see, is a graph of frequency against time. If you need to read that over one more time, please go ahead. It's sound production, recording, and sonography, all in one paragraph.

Frequency Modulation

The whistle, or "pure tone," is the bread and butter of acoustical theory, psychoacoustic research, and western music—and I don't mean country and western "music." The simplest process by which birds dress up their sounds is *frequency modulation*, which produces the changes in pitch trend that give us clicks, slurs, and warbles. It is accomplished by changing the shape of the syrinx, either with the muscles associated with the syrinx (Suthers 2004) or by changing the pressure in the air sacs that surround the syrinx (Beckers et al. 2003, Amador et al. 2008). The syrinx is a bird's voice box, which is located where the trachea (windpipe) divides into the two bronchi that lead to the lungs.

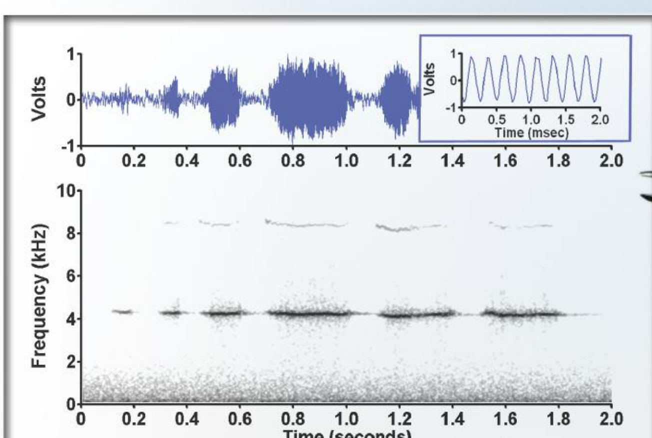
Raps, Clicks, and Slurs

Rotate the flat trace of the whistle almost 90 degrees and you get a *click* or *rap* (Fig. 4). The trace of a click can't be exactly vertical because that would indicate instantaneous pitch change, which is physically impossible. The membranes in a bird's syrinx can change their oscillation rates several kHz in ten milliseconds (1/100th of a second), though, which is very close to instantaneous, at least for our ears and brains. When stretched out, clicks have distinctive and often diagnostic fine structure. The birds probably hear this detail quite well. Many crack birders apparently resolve enough of the detail to identify birds accurately by these brief call notes. Sonograms offer hope to the rest of us.

A rap, unlike a click, is truly vertical on a sonogram, because it is actually a very brief *chord*, discussed later in this

Fig.3. Shown here are whistles of a **Mountain Chickadee** from Dolores County, Colorado, 27 April 1982. This sonogram has very high frequency resolution (at the expense of temporal resolution), so you can see just how close this male came to whistling a perfectly pure tone. Was he trying to? The gray spackling at the bottom of the sonogram is low-frequency noise, compliments of the wind. Had it been removed with a high-pass filter, the zero line of the waveform (in blue) would have been a smooth line rather than a jagged line. This wind does not obscure the target signal, and the clip sounds more natural with it included.

Sounds with flat sonograms have different tone qualities at different pitches (Pieplow 2007). To experience this effect, check out the *Birding* WebExtra that accompanies this article <aba.org/v42n4p63w1.html> and compare the real sound to the slowed-down and speeded-up versions. The former is "mellow," the latter, "sibilant" (or hissy).



Mountain Chickadee. *Bernalillo County, New Mexico; December 2009. Photo by © Alan Murphy.*

article. It is only brevity that makes clicks and raps visually and aurally similar, as very brief sounds all sound like clicks to us. When clicks are strung together you get a *trill*, also discussed later. Trilling with raps has a special name: "drumming."

Simple sounds between the extremes of the whistle and the click are slurs. Northern Cardinals are great at producing slurs that cross several kHz of frequency; study the sonogram on p. 58 and see for yourself. European Starlings are good at this, too. Slurs can be upslurs, downslurs, overslurs, or underslurs (Pieplow 2007), depending upon the frequency trend. "Warble" is a good generic term for a simple sound that changes pitch trend (that is, variation in frequency as time passes) more than once. Most of the phrases sung by American Robins (Fig. 2) are combinations of slurs and warbles.

Consider the familiar *pee-ah-wee* song of the Eastern Wood-Pewee (Fig. 5). Look at the thin line on the sonogram. It rises and falls quickly, then rises and falls again, then crawls up the scale for the better part of a second. You may not hear all the detail. I hear the first hump, if at all, as a sort of grace note. The *pee* part is the flat top of the second hump. The *ah* is the unemphasized descending trace, and the *wee* is the gradually rising line. For proof that the first hump is really there, play the half-speed version, which you can listen to on the ABA website <aba.org/birding/v42n4p63w1.html>. Then I think you will hear it. If not, play the fifth-speed version.

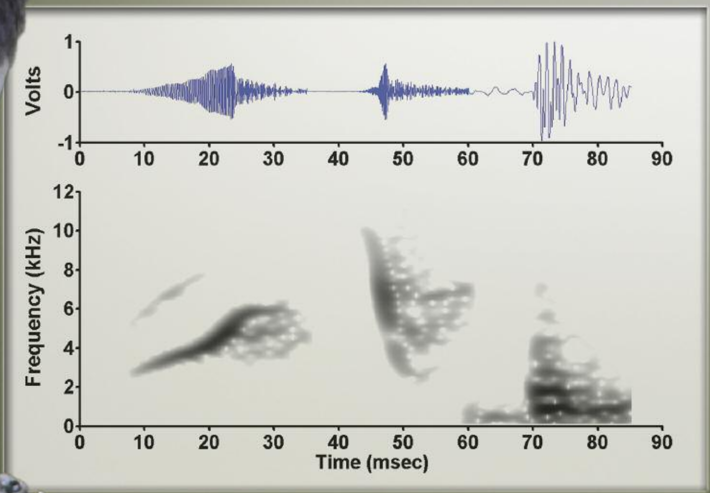


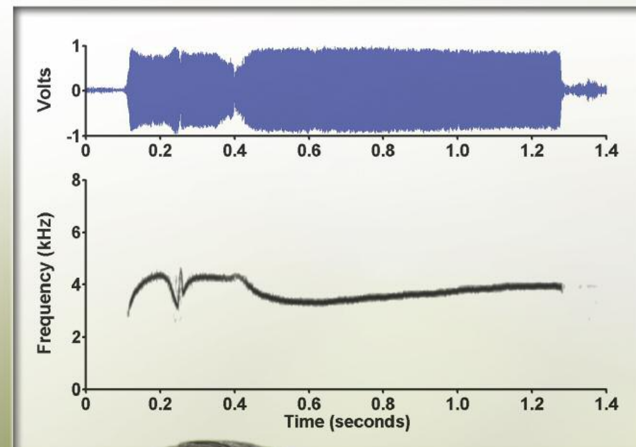
Fig.4. Here are two *clicks* and a single *rap*. The rising click is by a **Buff-breasted Flycatcher** from Cochise County, Arizona, 23 April 2003. The descending click is by a **Dark-eyed Junco** from Lane County, Oregon, 25 May 2006; the junco's click is "drier" because of greater frequency range and briefer duration. Rising clicks sound as if they end in the consonant "t." Falling clicks sound relatively "thick." Clicks are voiced sounds.

Because birds have a size-related minimum frequency at which their sound-production membranes can oscillate, the minimum frequencies usually exceed those of raps, which are percussive sounds. The energy of a rap is delivered to an external oscillator, such as the gutter on a house, instantaneously. The energy is quickly dissipated by the oscillator, as you can see on the waveform. Nevertheless, it still has a fundamental frequency, a low one, which you can estimate from the seven cycles between 70 and 80 milliseconds. This rapper is a **Red-naped Sapsucker** from McKinley County, New Mexico, 4 July 2006.

Dark-eyed Junco.
Victoria, British Columbia; May 2007. Photo by © Glenn Bartley.

Fig.5. This warble is the familiar *pee-ah-wee* song of an **Eastern Wood-Pewee** from Robeson County, North Carolina, 2 May 2009, illustrating simple *frequency modulation*. The frequency modulation in this sound develops more slowly than in most bird songs, but is still too quick for most of us to resolve the first overslur in the bird's song. The spike just past 0.2 seconds is not a usual feature of this song-type, but it is used elsewhere in the repertoire of this species. Bird sounds often have amplitude gaps, such as the one here at 0.4 seconds, that go unnoticed by human ears.

In this case, I think the gap has an evolutionary explanation. I suspect this song-type was derived by concatenating the initial part to the rising whistle that is used on migration by both North American wood-pewees. I haven't seen a sound equivalent to the *pee-ah-wee* in other species of *Contopus* flycatchers, so I think this combination occurred with or since speciation of the Eastern Wood-Pewee.



Periodic Frequency Modulation

Now let's look at a special kind of frequency modulation, called *periodic frequency modulation*. It produces a zigzag trace on the sonogram, as in the *bzew* call of the Western Wood-Pewee (Fig. 6). The zigzags look like a waveform, but they aren't. They do, however, exhibit a characteristic *modulation rate* (133 Hz) and *modulation depth* (around 500 Hz). This means the sonogram produces 133 zigzag cycles per second. The modulation depth is half the frequency range covered by each zigzag. These wood-pewees are modulating a carrier frequency that we can't see, so I have indicated its frequency contour with a red line. We know there really is a carrier frequency under there because sometimes the bird doesn't modulate and the pure whistle comes out. It is very similar to a call of the Eastern Wood-Pewee that is seldom modulated. Absence of buzz, therefore, is not a diagnostic characteristic of Eastern Wood-Pewee (Kaufman 1990). I know; I've bitten on that one.

The rate and depth of periodic frequency modulation are diagnostic in the introductory notes of the *chick-a-dee* calls of three species of *Poecile* chickadees (Fig. 7). The introductory "A" notes are "smooth" in the Mountain Chickadee, as in Black-capped and Carolina chickadees. In the Chestnut-backed Chickadee, these notes carry several cycles of sawtooth frequency modulation. The same is true of the Mexican Chickadee, but it sports much deeper modulation. Boreal Chickadee, thought to be the closest relative of Chestnut-backed, shows very slight or no modulation. It seems plausible that in chickadees the carrier frequency contains the information needed for communication among individuals, whereas the degree of periodic frequency modulation, or "buzziness," encodes species identity. Indeed, it seems to be a rather easy trick, evolutionarily, to add "buzz" to otherwise similar sounds. This form of frequency modulation helps us distinguish Mexican from Eastern

Eastern Wood-Pewee. *Scioto County, Ohio; May 2004. Photo by © Robert Royse.*

Whip-poor-wills; Yellow-throated, Plumbeous, and Cassin's vireos from Blue-headed, Philadelphia, and Red-eyed vireos; and most tanagers from robins. Perhaps it helps them do the same.

Harmonics and "Chords"

Now we move from simple sounds that can be represented by a single continuous line on a sonogram—albeit a wavy line in the case of buzzes—to those that are represented by multiple, concurrent traces. I call them *chords*. In music, chords are several sounds played together, either by different instruments or by different strings on, for instance, a guitar or piano. Individual birds can produce several sounds at once, too, using several mechanisms. Let's go through the possibilities, starting with the simplest.

I can synthesize a sound on my computer with a sine wave, and its sonogram will have just one straight line, like the dark line at around 4 kHz on the sonogram of the Mountain Chickadee whistle (Fig. 3). You will notice, however, that the chickadee's sonogram has a second, fainter trace between 8 and 9 kHz. This is called a harmonic. *Harmonics* are the natural result of the way mammals, birds, and frogs produce voiced sounds, which involves modulating (there's that word again) a stream of air with a vibrating membrane. The membrane vibrates at a frequency called the fundamental, but the resulting sound contains additional, concurrent tones at frequencies equal to integral multiples (for example, 2× or 3×) of the fundamental. Notice that the wobbles in the harmonic are more pronounced because every frequency change in the second harmonic is twice that of the fundamental. As a result, unless the fundamental is flat, the harmonics are not going to be parallel to it.

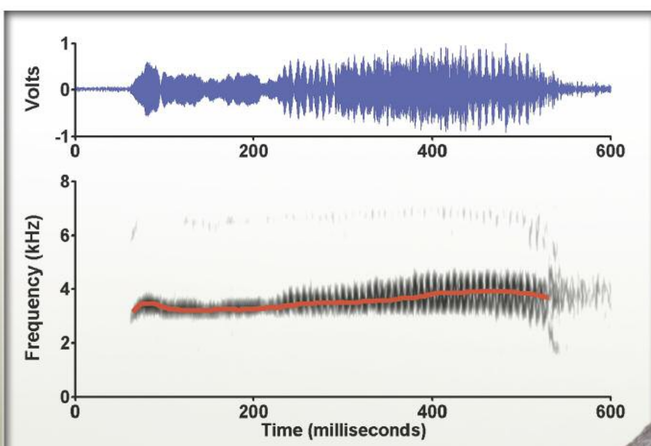


Fig.6. *Periodic frequency modulation* is illustrated by the *bzew* call of this **Western Wood-Pewee** from McKinley County, New Mexico, 12 August 2006. The bird superimposes a regular, "periodic" variation in frequency (pitch) on a carrier frequency, approximated by the red line. The way a bird produces this overlay has not yet been investigated by researchers, but note on the oscillogram that the sound is also amplitude-modulated. Play the slowed-down versions <aba.org/birding/v42n4p63w1.html> to get a better idea of what is going on. You may be able to sing the tenth-speed version.

This call type grades from buzzy, like this one, to a clear rising whistle, which is similar to a call of the Eastern Wood-Pewee. The buzz is elective. Many species have call types that have been given separate names by naturalists, yet are only modulated vs. unmodulated versions of the same vocalization. Of course, that doesn't mean they sound the same to the birds.

Western Wood-Pewee. *Kern County, California; June 2009. Photo by © Joe Fuhrman.*

Researchers who study sound production in birds generally think that the frequent absence of harmonics in bird sounds results from active filtering out of the harmonics. Recent research has confirmed this for the coos of Ring Doves (Beckers et al. 2003) and the slurs of Northern Cardinals (Riede et al. 2006); see Fig. 8. ("Ring Dove" is the name given to one of the domesticated populations of the African Collared-Dove.) My favorite example of a filtered bird sound is the *tseep* call of the Verdin. If you listen carefully, it seems complex, and slowing it down reveals that it has two parts (Fig. 9a). Except it doesn't. Clear recordings show that it is a single warble that falls, levels off, falls more, and levels off again (Fig. 9b). A "band pass" filter eliminates the sound above and below a certain "band" (3.5–7.5 kHz in this case), thereby emphasizing the fundamental for the first part of the sound. As the fundamental falls to around 2.0 kHz, however, it is mostly filtered out. The second harmonic then occupies the selected band, and gives us the second "note" of this one-note call. Now why do you suppose they do that?

For that matter, why do birds bother with filters at all? Especially when other species seem to go out of their way to produce harmonics, or "partials" that mimic harmonics, by means both honest and perhaps otherwise. Wood-

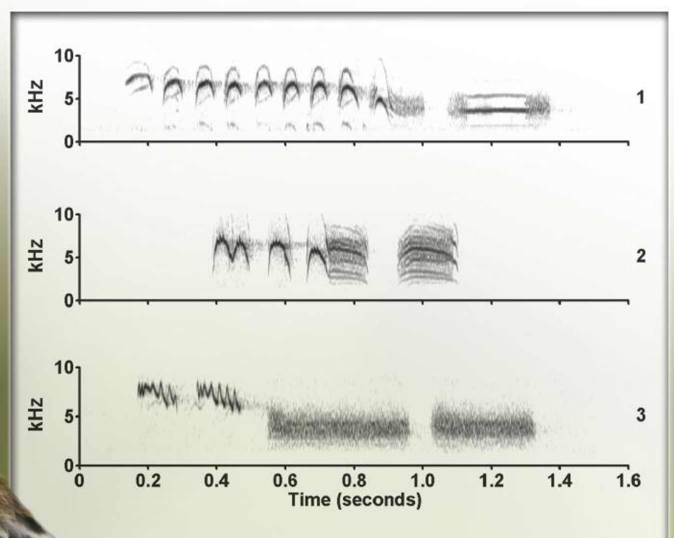
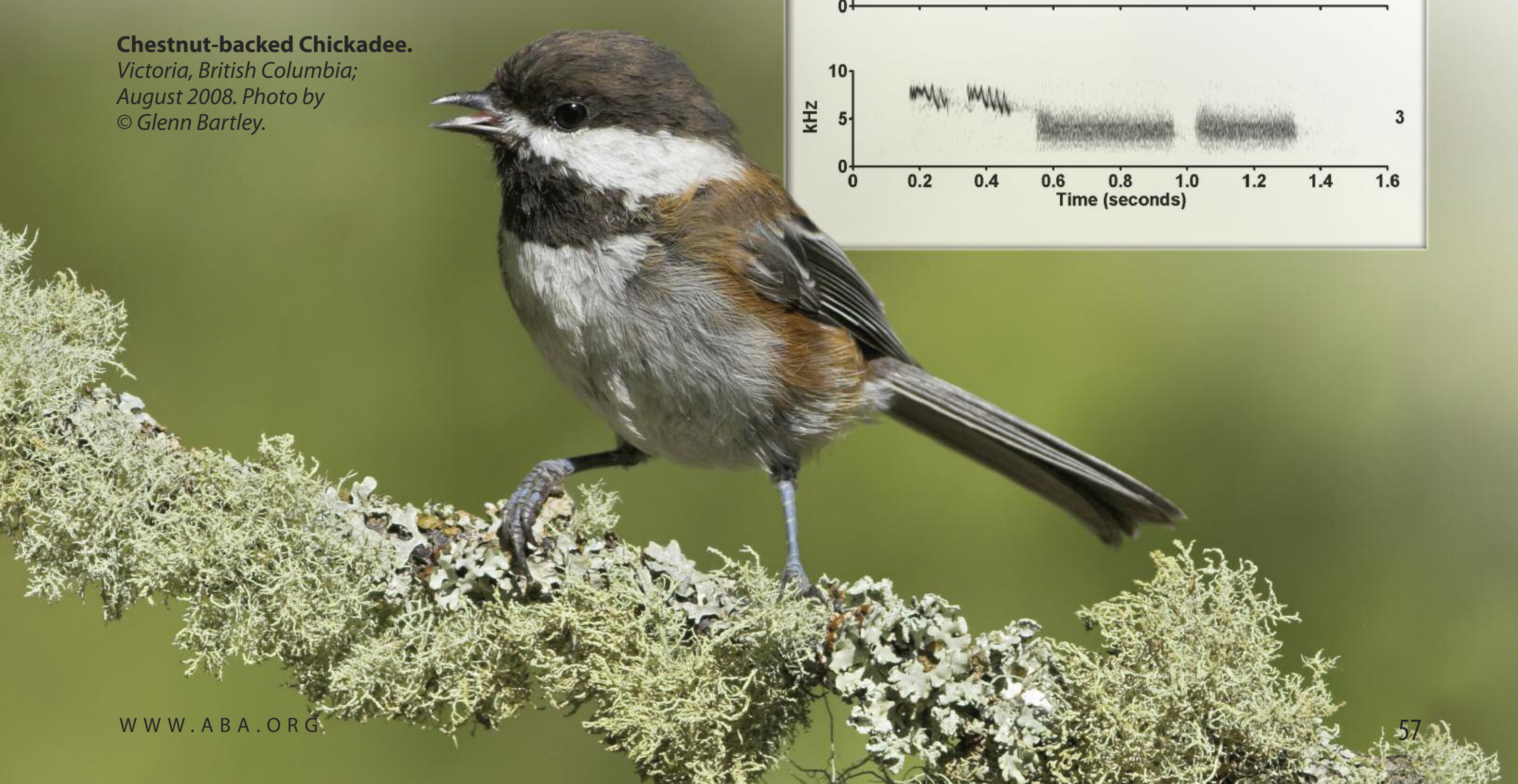


Fig.7. Shown here are the *chick-a-dee* calls of three chickadee species: (1) **Mountain Chickadee** from Dolores County, Colorado, 27 April 1982; (2) **Chestnut-backed Chickadee** from Lane County, Oregon, 16 April 2009; and (3) **Mexican Chickadee** from Cochise County, Arizona, 19 June 1995. These calls are "homologous"—that is, they have evolved from the same call in the common ancestor of these and other *Poecile* chickadee species. Note the similar pitch trend—it's overslurred—of the introductory notes in all three; to see this result, ignore the sawtooth frequency modulation in the latter two. Note, too, the overall similarity of the long, broadband terminal notes, which occupy rectangular spaces on the sonogram, despite the very different fine structure within those rectangles.

Support for the two-voice intermodulation model of sound production (Nowicki and Capranica 1986) is provided by the faint traces (these are "difference tones") below 2.0 kHz in Mountain Chickadee and the nonharmonic ratios of the frequencies of the bands in the final two notes of Chestnut-backed Chickadee. The dramatic shift from pure tone with harmonics to noise in Mountain Chickadee is a *nonlinear effect*. This result suggests that the noisy *dee* notes of Mexican Chickadees are generated by a chaotic mechanism, too.



Chestnut-backed Chickadee. *Victoria, British Columbia; August 2008. Photo by © Glenn Bartley.*

peckers, accipiters, chickadees, Red-breasted Nuthatches (Fig. 10), and Zebra Finches all produce stacks of partials with an interval of a few hundred Hertz. Why? Physiological research on humans has shown that the cochlea, the sound reception organ in our inner ear, faithfully registers the separate frequencies of such sounds (Hartmann 1998). But our brains do not transmit all that information to our consciousness. Stacks of partials, whether harmonics or not, are heard as composite sounds. That's why I think of them as chords. But research in Robert Dooling's laboratory at the University of Maryland has shown that Zebra Finches and Budgerigars are much better at detecting mistuned harmonics than humans. This suggests that, at least in these species, there is some benefit to the signaler in restricting the partials to harmonic ratios. Dooling's laboratory birds are also better than humans at resolving some temporal details of sound. No wonder so many bird vocalizations sound alike—to humans.

Not only do our brains get incomplete information, but so do our sonograms. There are several distinct mechanisms by which birds can produce sounds with stacks of partials. The most straightforward of these is to produce a low fundamental, say 0.5 kHz, with many true harmonics. That appears to be the method used by the Cooper's Hawk (Fig. 10, first three notes).

Northern Cardinal. *Galveston County, Texas; April 2009. Photo by © Alan Murphy.*

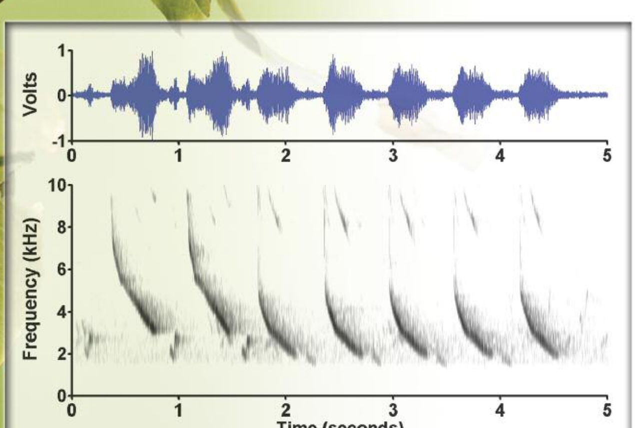


Fig.8. A **Northern Cardinal** from Buncombe County, North Carolina, 20 March 2003, sings alternating slurs and clicks. Cardinals use one side of the syrinx for the higher part of the slur and the other side for the lower part. They have to learn to align the contributions from both sides so the result sounds like one continuous note. Older males are better at this, which may have consequences for female mate choice (Suthers 1999).

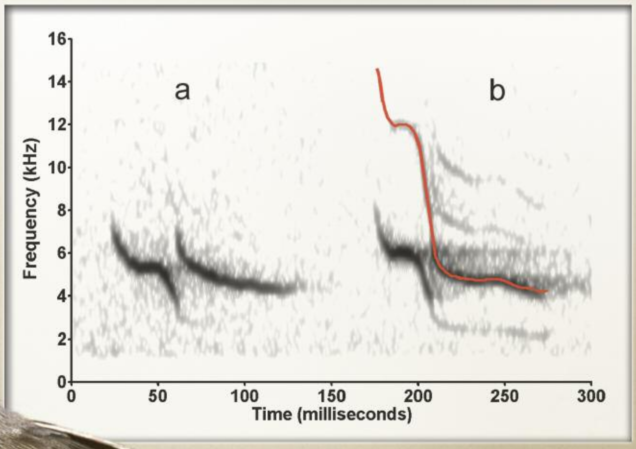
The transition at 5.5 kHz is slightly misaligned in the first slur. The frequency range of the final five slurs suggests they were produced by the left side only. The sonogram also illustrates the tracking filter of the Northern Cardinal (see Riede et al. 2006). The faint traces above 8.0 kHz are third harmonics; the second harmonics have been completely filtered out.

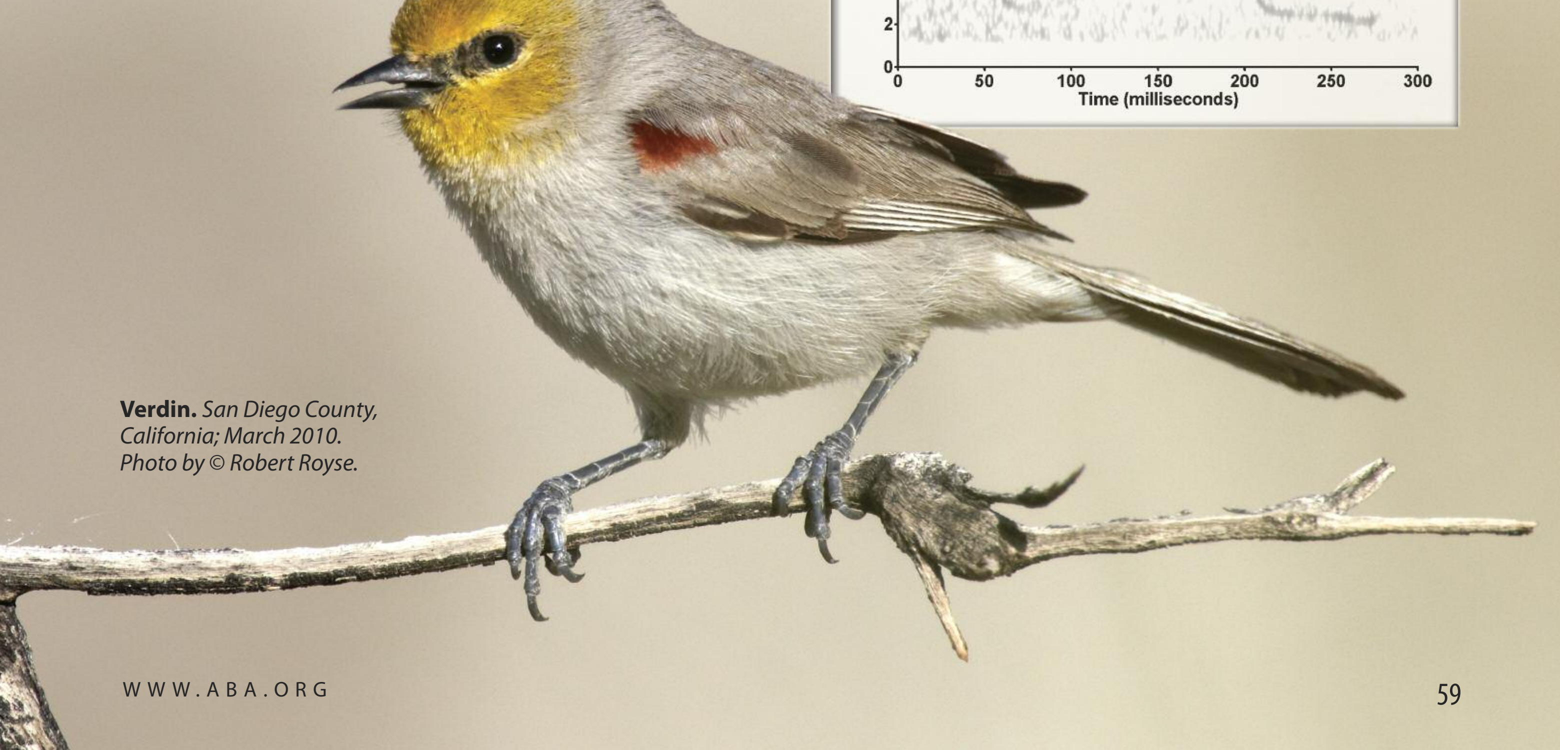
Amplitude Modulation
Another way to make a chord is to produce "sidebands" through amplitude modulation ("AM") of a much higher fundamental. Amplitude modulation is called *tremolo* in human singing. In the one species for which a mechanism has been discovered (Ring Dove), it is accomplished by regularly opening and closing a valve that cuts off some or all of the air flow (Beckers et al. 2003). If the resulting sound waxes and wanes in amplitude, say, 300 times per second, its sonogram will have sidebands 0.3 kHz above and below the fundamental (Fig. 11). Adding amplitude modulation, like adding frequency modulation, is an easy way to produce recognizably different tone quality.

Birds can make fundamentals and sidebands look like harmonics by modulating amplitude at a rate that divides evenly into the fundamental. Harmonics can have sidebands, too. A fundamental above 2.0 kHz, with sidebands above and below each harmonic, appears to be the way Pileated Woodpeckers produce their stacks. Including silence in each amplitude modulation cycle produces additional sidebands at double, triple, etc., the modulation rate. The result looks like a low fundamental with many harmonics, except that the pseudo-fundamental is often faint or missing. The Red-breasted Nuthatch is a candidate for this mechanism because its lower partials are often faint (Fig. 10, last note). But those partials could also have been attenuated by a filter. Additionally, a mechanism for producing low-frequency sounds (by "pulsing" the output of the syrinx) has recently been discovered (Jensen et al. 2007).

Birds' Two Voices
A more complex mechanism of amplitude modulation, employed by chickadees, was demonstrated experimentally a quarter century ago in a pioneering experiment by Nowicki and Capranica (1986). The familiar *dee* note of

Fig.9. This is the *tseep* call of a **Verdin** from LaPaz County, Arizona, 25 January 2003. The sonogram at left (a) is typical, showing a call that appears to be composed of two distinct notes. The sonogram at right (b) is from a recording made at close range, showing the true nature of the call. The fundamental descends, levels off, then descends and levels off again. The "second note" is actually part of the second harmonic of a continuous note. The two-note effect is produced by filtering out most of the energy below 3.5 kHz and above 7.5 kHz. The harmonic relationship of the partials is confirmed by the red line, which was produced by tracing the first harmonic—that is, the fundamental, which is the lowest partial here—and then multiplying all frequency values by two. Third and fourth harmonics are also visible in (b).





Verdin. *San Diego County, California; March 2010. Photo by © Robert Royse.*

Cooper's Hawk. *Cape May, New Jersey; October 2007. Photo by © Jim Zipp.*

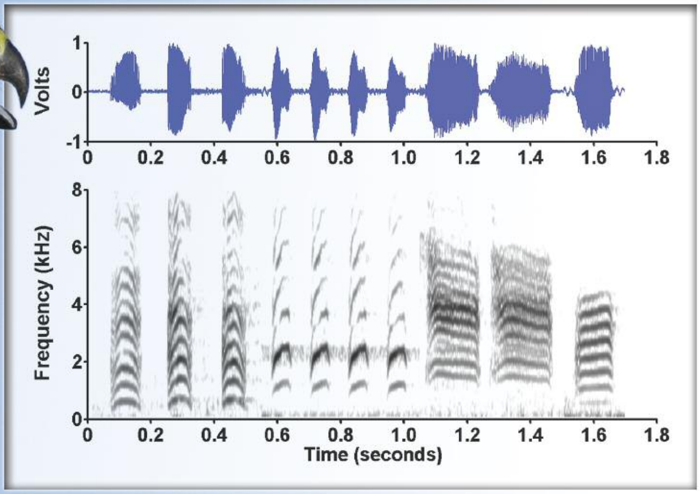


Fig.10. Shown here are the densely banded notes of a **Cooper's Hawk** (first three notes) from Modoc County, California, 26 June 2009; a **Pileated Woodpecker** (next four) from Charleston County, South Carolina, 24 May 1997; a **Black-capped Chickadee** (next two) from Lane County, Oregon, 16 April 2009; and a **Red-breasted Nuthatch** (last note) from Lane County, Oregon, 9 September 2008.

Inspection of waveforms suggests that the lowest band is the true fundamental of the Cooper's Hawk sound but that the Pileated Woodpecker's fundamental is the second-lowest band. For the Pileated Woodpecker, then, the first and third bands are sidebands. The Black-capped Chickadee's notes are clearly the product of two voices, probably the lowest two bands, because some bands rise while others fall. The faintness of the lower bands of the Red-breasted Nuthatch's note suggests that they are sidebands rather than harmonics, but the waveform does not support this interpretation.

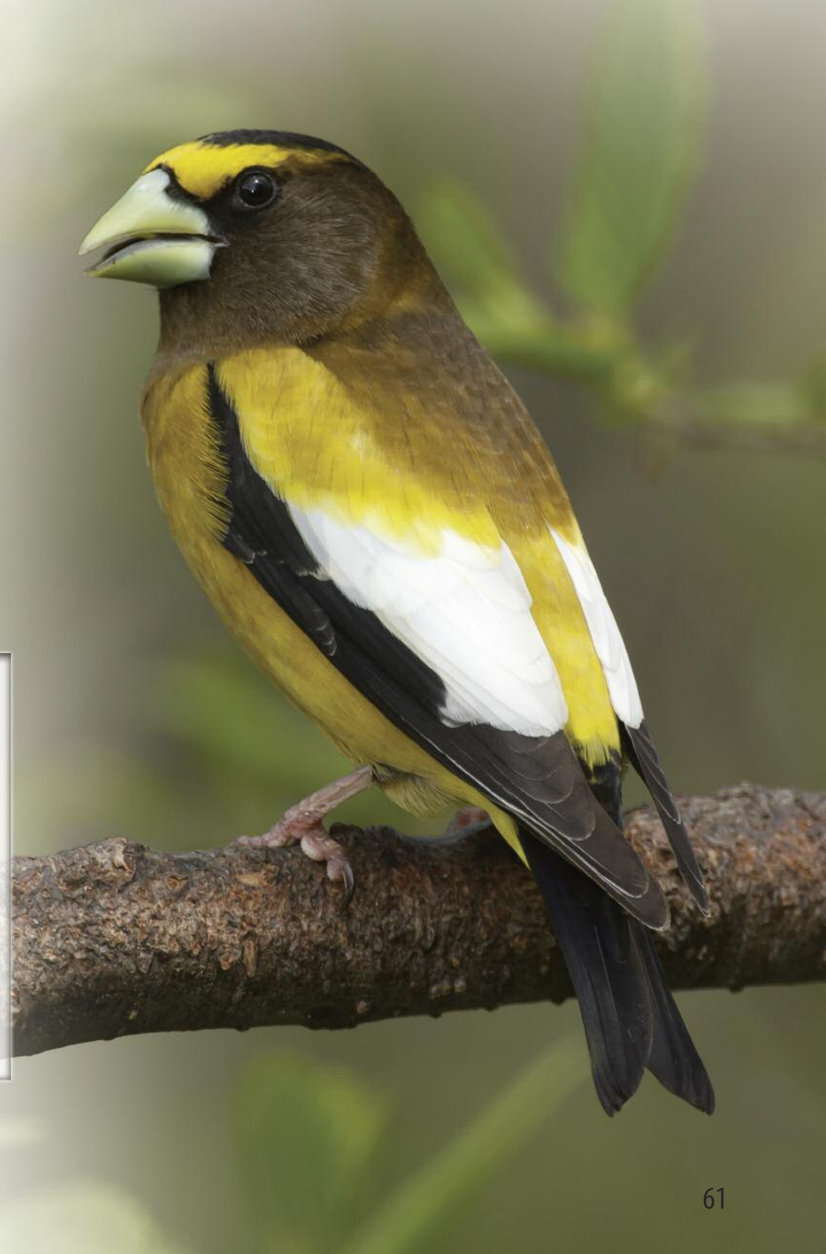
the Black-capped Chickadee had been described in an early treatise on bird sound (Greenewalt 1968) as a stack of harmonics above a fundamental at 0.4 kHz. Ironically, Greenewalt was among the first to propose that birds have two voices—that is to say, that the two sides of the syrinx can oscillate independently. Nowicki and Capranica not only confirmed the existence of independent phonation on the two sides of the syrinx, but they also showed that chickadees tune the two sides to be approximately 0.4 kHz apart—one at around 1.6 kHz and the other at around 2.0 kHz. The resulting stack of partials gives the impression of a fundamental at the relatively low frequency of around 0.4 kHz. The harmonics of these two fundamentals accounted for most of the bands on the sonogram, but not the ones below 1.6 kHz. Those were accounted for by a hypothesized mechanical connection between the two sides of the syrinx, which produced sum and difference tones. This mechanism has recently received independent support (Zollinger et al. 2008). As Nowicki and Capranica pointed out, not all chickadee *dee* notes have perfectly spaced partials. The examples in Fig. 10 could not have been made by a single oscillator, even with amplitude modulation.

Rod Suthers' lab at the University of Indiana has produced many examples of independent sound production by the two sides of the syrinx. The most startling to me is the way cardinals produce slurs (Fig. 8). The higher part of each slur is produced by the right side of the syrinx, and the lower part by the left side. Lining them up perfectly takes practice. It's one of the ways older males prove their mettle (Suthers 1999).

Advanced Sound Production: Nonlinear Phenomena and Other Stuff

We have covered simple and periodic frequency modulation, amplitude modulation with sidebands, and two-voice phenomena. Have you had enough? Don't say yes, because now we move from the domain of the merely complex to the realm of the downright weird—so-called *nonlinear phenomena*. A sound may change frequency instantaneously (try it, it's not easy), or a sonogram may sprout extra partials between the harmonics, again instantaneously, or a nice pure tone will change to "noise," instantaneously. That's what nonlinearity is all about—small increments of input producing huge changes in output. In animal sound, it is the biomechanics of the sound-producing structure itself, rather than tuning and modulation of the oscillating membranes, that is thought to allow these effects (Zollinger et al. 2008). Let's take a look at a couple of them (Fig. 12).

Shorebirds produce haunting pure whistles that seem to evoke the open spaces they inhabit, but they also deploy all the tricks in the nonlinear bag. The period of a wave form is the duration, in time units, of a single cycle of its



Evening Grosbeak. *Chippewa County, Michigan; May 2006. Photo by © Bob Steele.*

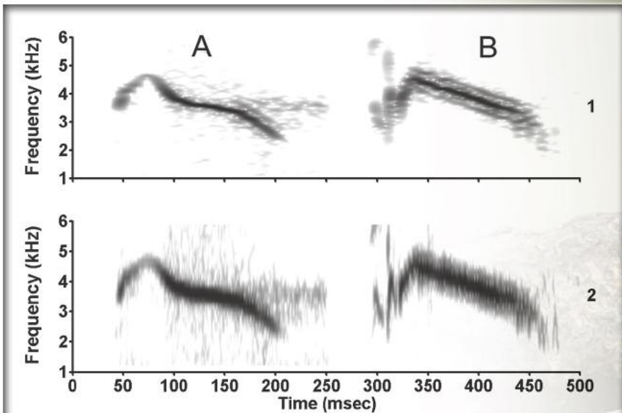


Fig.11. These are the flight calls of **Evening Grosbeaks** from (A) Lane County, Oregon, 17 April 2009, and (B) Tompkins County, New York, 28 February 1988. The call of the Oregon bird is a smooth overslur. The bird from New York whistles a similar tune, but the sound is amplitude-modulated, resulting in the sidebands seen at top right. This is a narrow-band sonogram, emphasizing frequency resolution. The wide-band sonogram—at bottom right—of the same sound yields better temporal resolution, as seen in the clear tick notes at the beginning of the call.

Every sonogram is a tradeoff between temporal and frequency resolution (Beecher 1988). Neither version is more correct than the other. Regardless, sidebands can be thought of as "field marks." The degree of modulation seen here illustrates geographic variation in the Evening Grosbeak, and these vocal differences correspond to different subspecies of the Evening Grosbeak (Sewall et al. 2004).

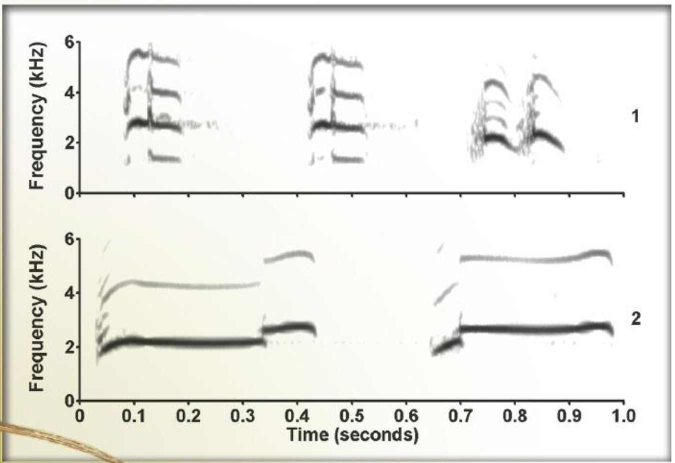
Recording from New York courtesy of © Lang Elliott, NatureSound Studio.

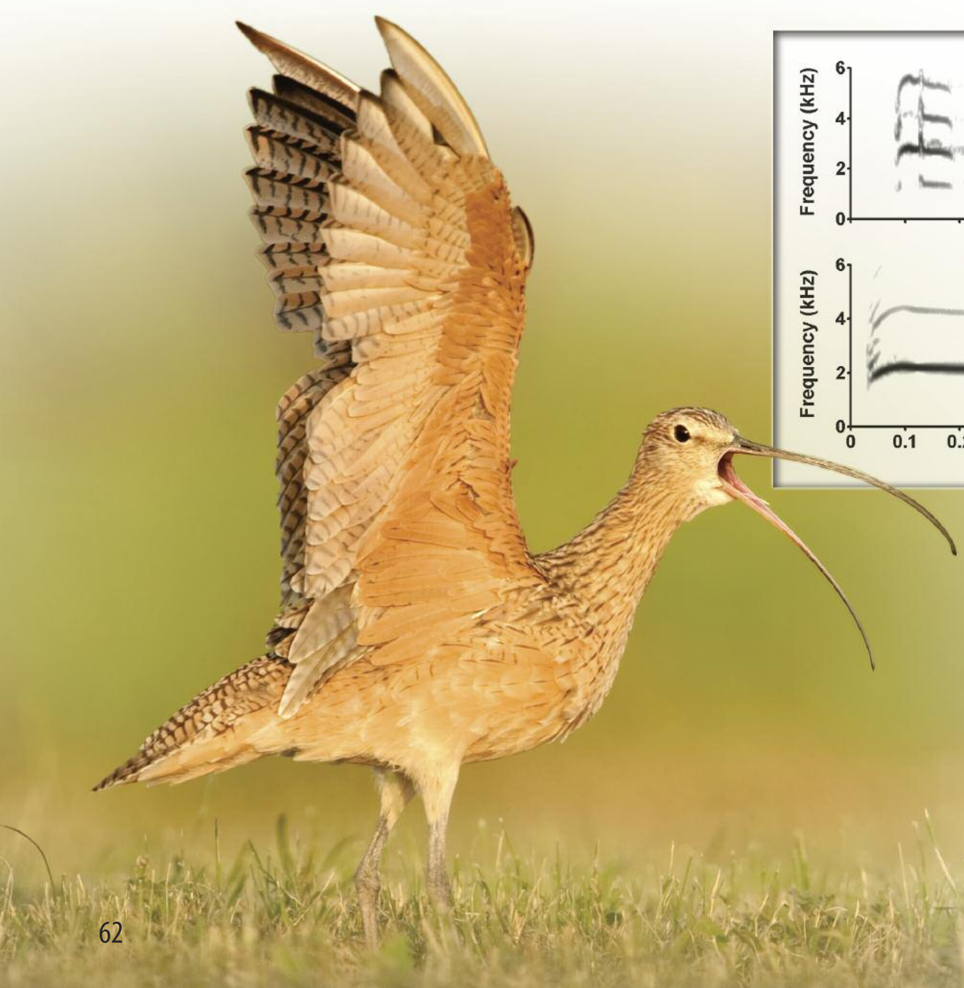
oscillation. *Period doubling* is a special case of amplitude modulation, in which the sound becomes fainter every other cycle. Because the distance between the low peaks (or high peaks) is twice that between adjacent peaks, the period is doubled, and that halves the frequency. This modulation, which must be very easy to do, produces sidebands halfway between preexisting harmonics (Fig. 12, top). Period doubling is a popular trick in hawks and shorebirds, who like to perform this maneuver in every note of a call. It enables them to change apparent pitch in each note without changing the fundamental frequency of the note. Listening to the slowed-down call of a Greater Yellowlegs makes this clear (Fig. 12).

Baby humans seem to enjoy using their lips as sound-producing oscillators. When, a little later in life, human children blow vigorously through vibrating lips, producing a "raspberry," it may sound less pleasing to others. A raspberry, though, is just a whistle that has been overdone, making the sound "chaotic." It's essentially what birds have done when you see a nice thin trace turn to a smudgy dark band on your sonogram. There are snippets of this "low-dimensional chaos" in the shorebird whistles shown in Fig. 12. It's also found in the scolding calls of small passerines. The *dee* of the Mexican Chickadee never shows any bands. They are always blocks of noise. I think the Mountain Chickadee can show us what's going on with the Mexican

Fig.12. Many sandpipers produce "chaotic" whistles. Panel 1 shows two calls given by a **Greater Yellowlegs** from La Paz County, Arizona, 25 January 2003, followed by two quick notes given by a **Long-billed Curlew** from Harney County, Oregon, 17 June 2004. The yellowlegs' calls begin with noise, then transition abruptly to a fundamental near 3.0 kHz with a harmonic, and then abruptly add sidebands. The sudden switch is called "period doubling" because every other cycle of the wave form is reduced in amplitude.

The curlew notes in Panel 1 start with noise, or "low-dimension chaos," and then switch to two sidebands between the fundamental and harmonic. This is accomplished by reducing the amplitude over a three-cycle period (Zollinger et al. 2008). Interposition of two partials is also evident in the first of two *cur-lee* whistles of a **Long-billed Curlew** (Panel 2). Note also the abrupt changes in frequency in both whistles. Although these changes in frequency could be accomplished by switching from one side of the syrinx to the other (Fig. 5), it is more likely another "nonlinear effect." When listening to the Greater Yellowlegs' calls at one-fifth speed <aba.org/birding/v42n4p63w1.html>, note the dramatic drop in pitch effected by simply adding amplitude modulation.





Long-billed Curlew. *Galveston County Texas; September 2009. Photo by © Alan Murphy.*

Chickadee. Mountains can make nice stacks of partials, like Black-caps, but they usually don't. Mountains' *dee*s are typically very noisy, although they do have a trace of pitch in the noise. Fig. 7 shows a fairly frequent occurrence in Mountains: For a moment, the noise drops away, and you see a clean whistle. Sudden shifts between noise and periodic sounds are acoustic field marks of chaos.

Noise, incidentally, is common in bird communication. The chickadee's *dee* note is just one of many methods birds have discovered for producing as harsh a sound as possible. And these harsh sounds, by the way, may be the only ones designed for the ears of predators, such as us.

Trills

Earlier, we rotated a whistle 90 degrees and got a click. If we rotate a flat stack of partials, a chord, 90 degrees, we get a series of clicks. That's a trill. Woodpecker drumming is a special case of trilling. Trilling also includes the *kek-kek-kek* calls of accipiters and the rattle calls of woodpeckers and kingfishers (Fig. 10). In these cases, each note is resolvable. In the faster trills of some sparrows and warblers, the very brief notes are often spectrally complex (Fig. 1, bottom). This complexity imparts some tone quality to the total sound that can be helpful in identification. Technically, such trills are combinations of notes, a topic I'll explore in the forthcoming companion piece to this article. But very fast trills converge on buzzes, which just serves to remind us that, as complex as bird sounds are, you can morph one into another by simply varying one (or more) of only five parameters: fundamental frequency, frequency modulation rate, amplitude modulation rate, degree of nonlinearity, and post-production filter. Think about it. They can be so different, and yet all are related. Rather like their makers.

In the early decades of sonography (1950–1980), authors often published tracings of sonograms rather than the real thing, which must have seemed too messy and full of extraneous detail. With the benefit of a half century's advances, we can recognize their unintended errors: faithfully rendering extraneous sounds, editing out details that they didn't understand or that seemed artificial, producing pictures of sounds that could not have been made. As we go forward, knowing something about how birds produce their complex sounds will help us sort real sounds from artifacts on these immensely useful sound pictures. I hope this article has advanced that goal for you, and I hope it will contribute to your enjoyment of sound pictures and thus the sounds themselves. All told, birds are acoustic virtuosos. And they're not bad at grammar, either. That's another topic entirely. Watch for it later this year in *Birding*.

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