

Artificial anuran chorusing

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Abstract. An artificial anuran chorus is built by simulating a population of signalers and their spatial distributions. Models and methods of the simulation are presented emphasizing the networked nature of a chorus, the consequences this has on its temporal structures, and how composers can use these models to rhythmically coordinate agent-based musical systems. Additionally, the paper discusses of the use of artificial life models in music as a literal imitation of nature.

Key words: acoustic communication, anuran chorusing, computational biomusicology, artificial life

1 Introduction

Frogs and toads (order *Anura*) can be found just about anywhere that water collects regularly. In large night-time assemblies, males call out rhythmically, producing loud washing choruses of advertisement to the unseen and often unheard females. Choruses commonly include a number of different species, each of whose sound signals fill spectral and temporal niches in the available acoustic bandwidth [2].

The structure of anuran choruses can be observed on several time scales. The signal interactions of neighboring callers produce pulses of synchrony and alternation as the callers mutually influence the timing of signal production. Groups of callers engage in competitive bouts lasting several minutes, stimulating other groups which can spread activation over a large area. These bouts concentrate in one or more periods during a twenty-four hour cycle, influenced by light, weather, and the presence of predators. In evolutionary time, female preferences move species through sonic fashions and the choruses change as genetics drift. It is a natural theme and variation that has been performed continuously for millions of years.

Studies of the signal interactions of anurans and insects have led researchers to develop a general model of an individual's calling patterns, based on a phase-resettable oscillator. In addition to explaining the empirical evidence of call timing adjustments, this oscillator model also allows for general predictions of patterns of synchrony and alternation in simulated choruses.

From an engineering perspective, chorus models can be useful to composers working with agent-based artificial life models in music, providing a biologically

plausible mechanism for the rhythmic coordination of musical machines. Alternatively, these models can be used to produce a different kind of artificial life based music altogether. Rather than a wholesale appropriation of the algorithms for creative inspiration, an artificial chorus can capture and reproduce a musical event from the natural world as a sort of generative nature recording; a literal imitation of life.

What follows is a description of the mechanisms implicated in natural chorusing as well as the models and methods used to create an artificial anuran chorus based on these mechanisms.

2 Acoustic coupling and synchrony in choruses

For small nocturnal animals such as insects and anurans, using sound to facilitate the business of life has been a winning strategy. The physical characteristics of the auditory channel in which they communicate shapes their interactions and thus the sound structures of their night-time choruses. Males and females both exploit sound for the advertisement of fitness as well as for mate location and selection.

Sound has a finite locality and directionality, and consequently, it can be a reliable indicator of proximity [12]. In environments where sight is limited by lack of light and vegetation, acoustic signaling by males facilitates the discovery of their location by females who make an approach in response. When the groups of signaling males become very large, the bandwidth with which to broadcast signals becomes scarce, sparking competition to be heard by females.

In response to the challenge of discriminating one fit call among many thousands, the females of many chorusing species have a perceptual bias toward the first call of a sequence from a group of signaling males. They preferentially orient themselves toward, and ultimately approach, the producer of leading calls [3]. Thus, this psychoacoustic *precedence effect* in females selectively favors males who are heard to produce such leading calls.

Another important property of sound with regard to signaling and communication is that it generally affects many individuals at the same time. Messages are broadcast indiscriminately to anything with the correct receiving equipment. So while the intended target of a signal may be a female, chorus participants unavoidably eavesdrop on each other's signals. This eavesdropping can be exploited in the competition to be heard first, and consequently, males have evolved to make call-timing adjustments to their own free-running call period in response to competitors in their immediate environment.

At its most extreme, call-timing adjustments can drive the chorus to lock around a regular pulse with each member of the chorus apparently coordinating their signaling in synchronous or alternating patterns. This *synchronous chorusing* is, in fact, not a coordinated effort, but rather an epiphenomenon of an acoustic coupling of between competing males, whose call-timing adjustments are shaped by female preference for leading calls [8].

Although the degree at which synchrony or alternation is expressed in a chorus ultimately varies from species to species, common neural mechanisms are believed to underlie the production of synchrony and alternation in many choral structures. Each individual signaler in a chorus is thought to have a neural oscillator, or pacemaker, that is responsible for triggering calls [8]. Thus, the seemingly complex sound of the anuran chorus, is the result of many small groups of acoustically coupled signalers.

Based on this description, signalers and their interactions can be modeled using a simple network of oscillators that govern an individual’s call-timing. The next section describes one such model.

3 The model

3.1 Bodies

The literature on anuran and insect communication describes a number of neural pacemaker models of varying complexity [6]. For the proceeding simulations, a basic linear model is used that was developed by Michael D. Greenfield and colleagues using data collected from playback experiments with the Neotropical katydid *Neoconocephalus spiza* [7] [8] .

To model call-timing adjustments, each anuran in the chorus is essentially a sawtooth oscillator with a free-running period (T) whose phase can be reset by the receipt of a stimulus signal. When the oscillator reaches its peak level, a “trigger” is sent that results in a call (x) after a short effector delay (t). In the presence of a stimulus signal (y) the free-running period of the oscillator is reset to its basal level and inhibited for the duration of the stimulus before the oscillator resumes at its natural free-running period. The effect of the stimulus is to either lengthen or shorten the time between calls depending upon where in the cycle the oscillator is reset. If the oscillator is reset on the ascending slope, the *concurrent* period (T') is lengthened. If the oscillator is reset on the descending slope, measured by r , the *next* call period is shortened (see Figure 1).

While this description could conceivably be modeled as a literal sawtooth wave, in a piecewise linear form, Greenfield et al have arrived at a computationally efficient and somewhat simple linear model to calculate the modified period (T'), describing the changes to call timing as influenced by a neighboring caller. The Greenfield timing model is as follows:

$$T' = s[(d + l/v) - (r - t)] + (T + \epsilon) + (y - x), \quad (1)$$

where T' is the modified call period after the receipt of a stimulus of length y from a neighboring caller. Here, d is the time elapsed since the focal male’s last call, l is the distance of the stimulus measured in meters and v is the speed of sound (344 m/s). A stochastic element, ϵ , is added to the call period to better match the reality of imperfect timing in organic pacemakers. The s parameter is

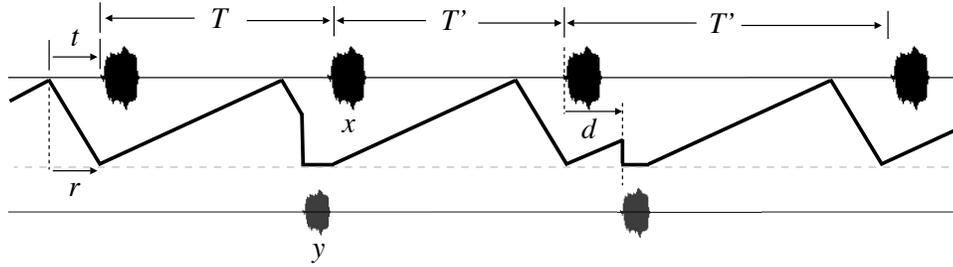


Fig. 1. Phase-resetting inhibitory oscillator showing signal triggering from the focal male (*top oscilligram*) and phase resetting and inhibition from an external stimulus (*bottom oscilligram*). Modified from the original which appears in Greenfield (1994) [7] and elsewhere [8][6]. See the text for further description and parameters.

the phase response curve (PRC) of the caller, which Greenfield notes regresses the response phase against the stimulus phase. It is this s parameter, discussed in the results section that has the most effect on the development of synchrony or alternation between neighboring callers. Together, the parameters in equation 1 account for effector delay, sound propagation, phase resetting, period inhibition, and oscillator rebounding after inhibition. For a more detailed description of the model, the reader is referred to the original model appearing in [8].

Of special note here is that when a stimulus is received during the descending slope of the oscillator, or r , the d parameter has a negative value. This is not immediately obvious from the equation above. It is calculated at the time a stimulus signal is received by subtracting the elapsed time since the onset of the last call from the difference between the current call period, T , and the effector delay, t . Thus the effect of a negative d is to shorten the *next* call period and a positive d to lengthen the *current* call period.

There are additional adjustments that can be made to equation 1 to account for the evidence that callers may not hear stimulus signals during their own calls, but for the sake of clarity, these modifications are not included in the current simulations.

3.2 The network

The elegance of the Greenfield timing model is that it describes both the body of the signaler as well as the affect of a stimulus when used in a network of signalers. When simulating a network of signalers using this model, distances are specified for each member of the chorus (given by l), as well as threshold of sensitivity to a neighbors signal. Otherwise the connectivity of the network can inadvertently be quite high, resulting in universal synchrony.

The sound of the stimulus is modeled to have its intensity decrease with the square of the distance from the source, following the description in [12]. In

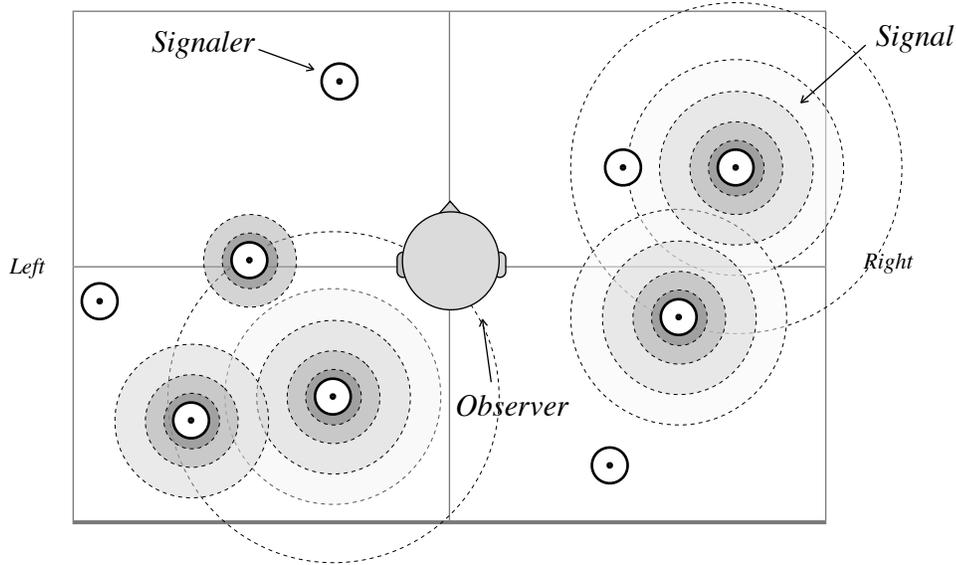


Fig. 2. *The chorus environment:* modeled in 2D space with the observer at the middle of the sound field. Concentric circles around the agents represent the instantaneous sound pressure levels of emitted acoustic signals.

this way, chorus members who are sufficiently far away can be ignored. In fact, there is evidence that chorus participant selectively attend to only a very few neighboring callers, presumably those that are the loudest, closest, or both [6]. Following this, each signaler “hears” only its few closest neighbors.

For a larger chorus participants are simulated in 2D (x,y) coordinate space, with the “observer” (in this case, the speakers) placed in the center of the simulation (0,0) and reproduced in a stereo field. Signals are panned right and left based on their positive or negative deviation respectively from the center point of the field on the x axis. Positive and negative deviation from the center point of the field on the y axis results in decreasing gain in both directions. Signalers are placed at random. While somewhat simplified, this gives a decent illusion of space. See figure 2 for a visualization.

The experiments performed in the following section use the Greenfield timing model described in equation 1 and concentrate on a pairwise interaction between only two coupled signalers to reveal the dynamics of the model before briefly describing the results of the larger, and decidedly more complex, network of signalers, in small randomized groups.

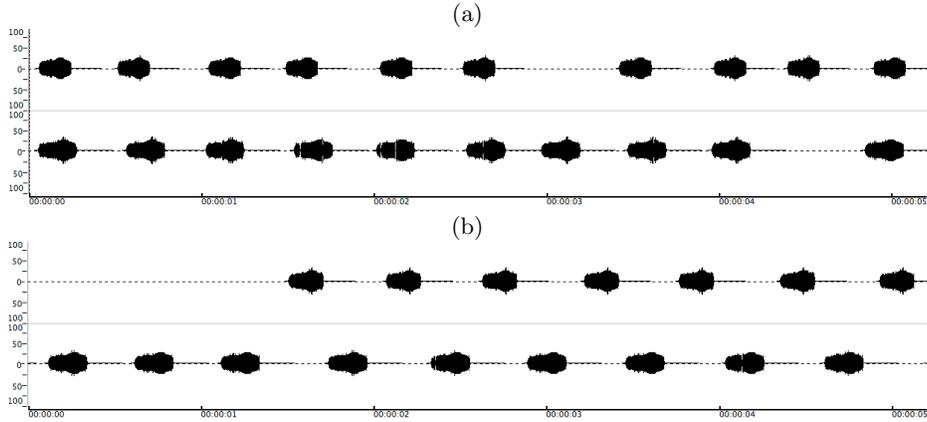


Fig. 3. Synchrony (a), resulting from $s = 0.9$, and alternation (b), resulting from $s = 0.1$, between two coupled signalers where $T = 500$, $t = 60$, $x = 50$, and $r = 100$. The effects of call-timing adjustments are readily visible.

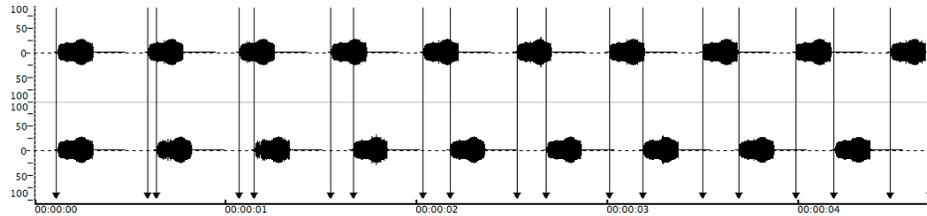


Fig. 4. An example of adaptive alternation between coupled signalers by setting d to the time elapsed since the onset of the last call. When applied to multiple signalers, this alternation forces the even distribution of signals over time, shortening each signalers call period. See text for a full description.

4 Results

4.1 Pairwise interactions

Using the model given by equation 1, two coupled signalers are simulated in a pairwise interaction. For each of the trial runs, all parameters are set to the following values, with only the PRC, s , varied between runs. $T = 500$, $t = 60$, $x = 50$, and $r = 100$ (all parameters are measured in milliseconds). Stochasticity for ϵ is kept relatively low at random value for each period around 30ms.

While each of the parameters affects the interactions on some level, it is the value of s , varied over the interval $[0,1]$ that has the most affect on whether synchrony or alternation develops. As s approaches 1, the interactions of the signalers become increasingly synchronized. This can be seen in figure 3 (a) where the value of s is set to 0.9. Conversely, when the value of s approaches 0,

the interactions move toward alternation, shown in figure 3 (b). These results confirm those reported by Greenfield in [8].

When the calculation of d is forced to be the elapsed time since the focal male's last call (ignoring where in the oscillation the stimulus falls), the resulting interaction takes on some very peculiar characteristics which effectively is an adaptive alternation of call periods. Not only is the alternation between calls assured, but it progressively moves there, the speed of period adjustment determined by the value of s . Lower values of s result in a slower adjustment of periods moving toward alternation and visa versa. This behavior results no matter where in each other's period the callers are coupled.

Interestingly, when applied to groups of signalers, each signaler adjusts its period so that the temporal space is completely filled with signals, each occupying its own space in the overall chorus. In this scenario, as signalers are added and subtracted from the chorus, each member's period adjusts accordingly by accelerating and decelerating call timing respectively so that all the calls are evenly spaced in time. While this unexpected effect is completely unnatural, it may be of interest to the composer for other productions and in the rhythmic coordination of multi-agent music systems.

4.2 An artificial anuran chorus

The experiments on pairwise interactions are extended to produce an artificial anuran chorus. Following the aforementioned evidence of a signaler's selective attention to only a few of it's closest or loudest neighbors, each signaler is coupled to only two or three other signalers, determined randomly by proximity. This selective attention keeps the connectivity of the network relatively low and avoids the unnatural conditions of an epileptic universal synchrony which results from a high connectivity. The value of s is also set randomly.

Each signaler is given energetic constraints which when reaching a threshold, cause the cessation of signaling for a random period. This makes sure that patterns of calling changed subtly as performers left and joined the chorus. The parameters of the model are adjusted to mimic the responses of the particular species desired. Given low connectivity, selective attention, and a variation of species and natural call periods, the artificial chorus sounds surprisingly natural. Bouts of synchrony and alternation are evident as groups of signalers couple dynamically. See figure 5 for a spectrogram of results. Audio files of artificial choruses are available at <http://unnature.org/frogs>.

4.3 Materials and Methods

For the pairwise simulation, the spring peeper, *Pseudacris crucifer*, was used because of its short and relatively monotone calls. For the chorus simulation, a group of species were chosen whose ranges overlap in the North Eastern United States and can be observed in choruses together. They are the Northern cricket frog *Acris Crepitans*, the gray treefrog *Hyla Chrysoselis*, the American toad *Bufo Americanas*, and the green frog *Rana Clamitans*. Samples were taken from

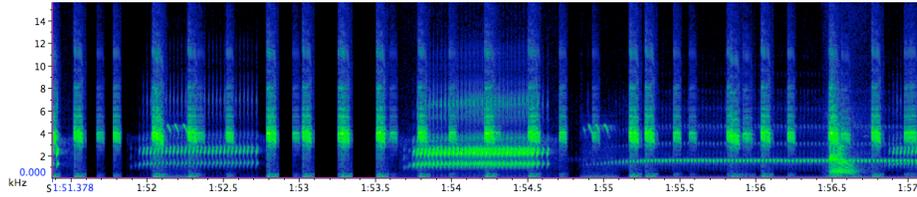


Fig. 5. Spectrogram of a small cross-section of an artificial chorus. Species were picked by region. Northern cricket frog (3-4kHz), gray tree frog (bands at 1.5Khz and 2.5Khz), american toad (2Khz), and a plunking green tree frog at approximately 1:56.

recordings made in the New York and New Jersey area [1] and call periods of the constituent species were estimated from the recording. Real-time simulation of chorusing models is written using the ChucK programming language [13] running on Fedora 6 Linux and Mac OS X.

Signaling was modeled as an event-driven architecture using the classic observer pattern [5]. Since this simulation is only concerned with a description of call interactions, and not all of the biophysical mechanisms of sound discrimination in a complex and noisy natural environment, this programming design pattern is considered appropriate.

5 Discussion

5.1 Synchronization tools for the artificial life composer

Composers have a rich palette of tools for the modeling of beat induction and synchronization. Models such as Adaptive Delta Pulse Code Modulation [4] and nonlinear systems of adaptive oscillators [10] are quite effective at synchronizing signaling agents. While these models are inspired by assumptions of a natural timing or a preferred tempo that *could be* biologically coded, they are essentially engineered solutions to the problem of period synchronization.

The Greenfield timing model is different from many other models of period synchronization in that its algorithm was formulated directly from empirical studies of rhythmically signaling animals, and then verified through comparison to a number of insect and anuran species known to engage in synchronous or alternating choruses. It is a true biologically plausible model of synchronization.

For the creative composer working with artificial life models, biological plausibility may not be a consideration. But for the researcher in biomusicology or the origins of music, there could well be benefits from the application of this model. Indeed, the chorusing of anurans and insects has already been suggested as a relative of our own music [11].

5.2 An imitation of life

While this model of chorusing might lend itself to an artistic license in application as a compositional aide or as creative inspiration, it can alternatively be viewed as a different type of artificial life music. Rather than an arbitrary sonification of artificial life algorithms, this attempt to realistically simulate an anuran chorus is a sort of biomusical realism, or possibly, a generative nature recording.

Unlike linear nature recordings, a simulation allows the composer to separate the sound event from place and time - hand choosing the species, their physical distributions, and their call periods. Of course, since there are known selection pressures on chorus participants, it is only a small leap of imagination to conceive of evolving artificial choruses.

5.3 Eulogy

Since 1970, scientists have observed precipitous population declines and outright disappearances of entire amphibian species. The extent of these declines and extinctions is without precedent among any other group of species over the last few millennia. [9]

Amid massive and abrupt changes to the earth's ecosystems it seems possible that we may lose some of these sound ecologies altogether with events such as the night-time chorusing of frogs and toads available only through recordings. But recording these systems requires more than a just a microphone and a stereo recorder. If these systems disappear and we only have linear recordings, we may find the document as lacking in depth as the taxidermy skins of extinct animals.

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