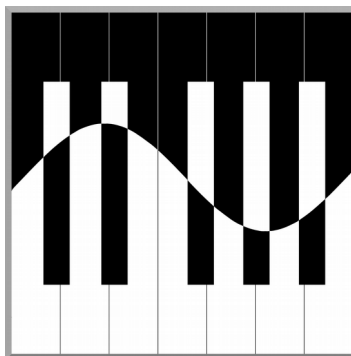# just Intonation

User Guide

Karolin Stange, Christoph Wick, and Haye Hinrichsen

Department of Theoretical Physics III
Faculty for Physics and Astronomy
University of Würzburg, Germany

just-intonation.org

just-intonation.org

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Motivation of the project

Intonation and temperaments

Are F♯ and G♭ identical notes? At least on a piano this seems to be the case since there is only a single black key for both of them. But for what purpose do we have two different notations?

If you are interested in music you probably know that F♯ and G♭ are *not* identical. In fact, conductors of choirs and orchestras insist that both notes have to be intoned differently. Only on keyboard instruments they are represented by a single tone.

This so-called *enharmonic equivalence* on keyboard instruments is one of the main achievements of the *Equal Temperament* (ET), which has established itself as the standard tuning system in Western music since the beginning of the 19th century. In the equal temperament the octave is divided into twelve equally sized semitones with the constant irrational frequency ratio $2^{1/12}$. The main advantage of the ET is the invariance of all frequency ratios under transposition (key changes). This means that a piece of music in C-Major, when played for example in D-Major, will be higher in pitch but apart from that no difference can be heard.

The simplicity and symmetry of the ET, however, can only be established at the expense of harmony. The reason is that justly tuned musical intervals have simple rational frequency ratios. Since the frequency ratios in ET are irrational, all intervals except for the octave are therefore slightly out of tune. For a fifth the deviation is still acceptable since $2^{7/12}=1.4983...$ differs from the perfect fifth 3:2=1.5 by only two cent[1], and the same applies to the complementary interval, the fourth. However, a major third in the ET with the frequency ratio $2^{4/12}$ differs from a perfect major third (frequency ratio 5:4) by almost 14 cent which is a huge and clearly audible difference.

With respect to harmony, the ET is probably one of the worst temperaments ever created by humanity. This is presumably one of the reasons why the ET, which has been known for much longer time[2], became a standard only in the 19th century since musicians of earlier periods were not yet ready to tolerate the resulting dissonances. In the last two centuries, however, Western societies became used to the ET and today the ET even begins to influence the music of other cultures. "*How Equal Temperament Ruined Harmony – and*

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1 In music theory a cent is defined as the frequency ratio of 1/100 of a semitone.
2 The ET was presumably first proposed by Aristoxenos of Tarent (300 v. Chr.) but then dismissed.

Why You Should Care" is the provocative title of a book written by Ross W. Duffin[3], who nicely explains how the listening habits of Western societies have changed over the centuries and how composers and musicians reacted to these changes.

The extreme opposite of the ET is a tuning scheme based exclusively on simple rational frequency ratios, referred to as *Just Intonation*. In its own reference scale just intonation is very harmonic if not even sterile, but unfortunately it does not work in other scales. For example, tuning a piano in just intonation with respect to the root C, music played in C-major would be perfectly harmonic while in most of the other scales it would be terribly out of tune. The same applies to modulations (intermediate key changes) which are present in virtually any kind of music. Thus, for good reasons, just intonation has the reputation of being absolutely impractical.
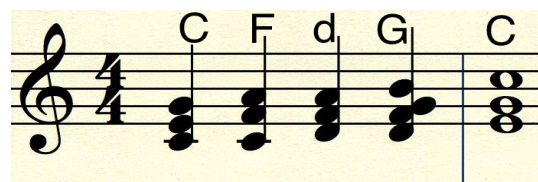
The trained ear of a musician is able to intonate its note justly with respect to the given keynote or a harmonic construct, no matter if it is in a choir or an orchestra. Clearly the intonation resulting from continual adaption will differ from the ET. With this knowledge the following quotation of the famous cellist Pablo Casals seems to make a lot of sense:

> *"Don't be scared if your intonation differs from that of the piano.*
> *This is because of the piano which is out of tune"*.[4]

In order to achieve a clean intonation, a choir faces two major difficulties. The first one is that most pieces of music, although written in a certain reference scale, modulate through various other intermediate keys. Therefore the so-called *chordal root*, the base frequency which just intonation refers to, changes frequently, meaning that the required pitch corrections relative to the ET vary with time.

The second difficulty is a pitch-drift through *harmonic progression* caused by an accumulation of tuning corrections over time, – a phenomenon that was already discovered by the renaissance mathematician Giovanni Benedetti in 1585. The harmonic progression is the main reason why even excellent choirs tend to drift away in pitch over time.

To understand how pitch drift in just intonation occurs due to harmonic progression let us have a look at the alongside example. Tuning the intervals in the sequence C-F-d-G-C justly, the resulting frequency ratio from the initial C to the final C would be given by

3   Ross W. Duffin, published by W. W. Norton & Company, Inc., New York (2007).
4   Pablo Casals, *The Way we play* (1972).

$$\frac{4}{3} \cdot \left(\frac{6}{5}\right)^{-1} \cdot \frac{4}{3} \cdot \frac{4}{3} = \frac{160}{81} \approx 1.975 < 2,$$

which is smaller than 2. This means that the final C would be by the factor 80/81 (-21.52 cent) lower as expected. This difference is called the *syntonic comma*. By repeating this harmonic progression four times the difference between the initial and the final sound adds up to almost a semitone. Such a pitch drift can occur with many different harmonic progressions, and the pitch can both increase and decrease, depending on the specific harmonic flow.

Dynamically adapting tuning schemes

So far we have seen that just intonation, statically tuned with respect to certain reference key, is completely impractical because it is out of tune in almost all other scales. On the other hand it seems that choirs and orchestras can get closer to a clean intonation by adding suitable tuning corrections. Is it possible to mimic this correction process algorithmically?

This question naturally leads to the concept of *dynamically adapting tuning schemes*, where the pitch of each tone is adapted instantly while the music is being played. The idea of dynamical tuning already came up in the early days of electronic keyboard instruments. Since then various implementations have been suggested, the most important ones being *Justonic Pitch Palette*[5], *Mutabor*[6], and *Hermode Tuning*[7]. Most of the existing algorithms determine the chordal root (base frequency) of a chord and then compute the pitches on the basis of rational frequency ratios. Another method is to classify chords by templates and to correct pitches selectively. Apart from *Hermode Tuning*, which is implemented in various synthesizes and even in real organs, it seems that none of these implementations has reached a wider dissemination that could challenge the predominant ET.

In this context, it is worth mentioning that just intonation also plays a role in a special branch of contemporary music, known as *microtonal* music.[8] The idea is to abandon a fixed musical scale and instead to explore the whole universe of microtones with continuously varying frequencies in between. In this respect rational frequency ratios play an important role, which led to a renewed interest in just intonation. For an average listener, however, microtonal music played in just intonation often appears to be strange and uncommon, and this is probably the reason why it has not yet reached a broader audience.

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5 Justonic Tuning Inc (Rex Weyler).To our best knowledge the Justonic website went offline in spring 2016.
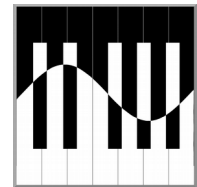6 http://www.math.tu-dresden.de/~mutabor/
7 http://www.hermode.com/index_en.html
8 See e.g. Center for Microtonal Music, http://www.huygens-fokker.org/activities.html

With *Just Intonation*, the software presented here, we would like to demonstrate that dynamically adapting tuning schemes may have a much larger range of applications even in the area of conventional music. We would like to convince the listener that just intonation is much more than a purely academic matter of small elites and that dynamical tunic schemes can be applied successfully to ordinary classical and contemporary music – music that most of us know and appreciate.

When hearing music in just intonation for the first time, you may have the impression as if it was somewhat unfamiliar and even partly out of tune. This is because all of us are accustomed to the ET since early childhood. However, listening repeatedly or playing by yourself on the touchcreen of a MIDI-keyboard you will be surprised how quickly our sense of hearing gets used to justly tuned intervals and perhaps you will begin to like their high degree of consonance. Then, returning to the ET, it is suddenly the ET which is perceived as being out of tune, – and in fact, it actually is.
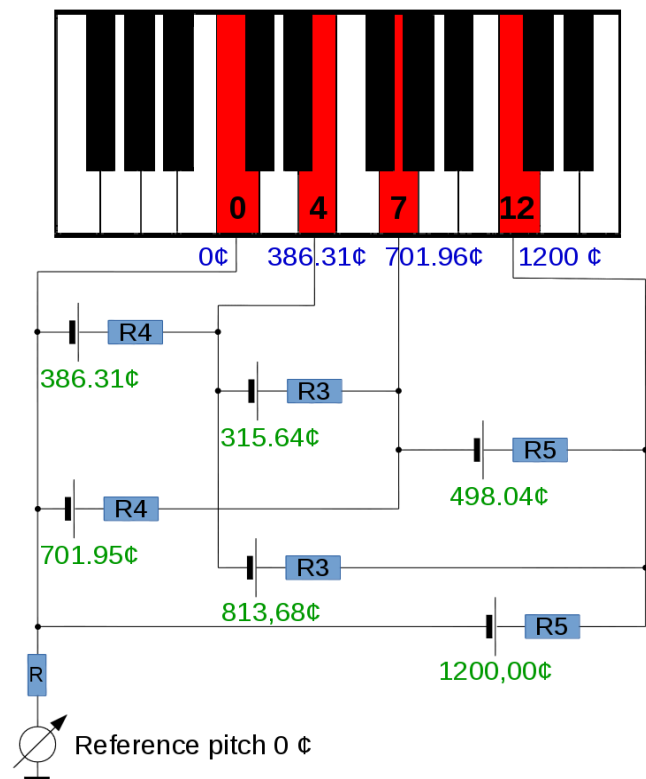
Just Intonation – Structure and Functioning

Just Intonation is a software package which consists of the following components:

- A microtonal sampler that can play sampled sounds in any pitch.

- A microtonal tuner which tunes music in dynamically adjusting just intonation and other temperaments.

- An interface for MIDI input and output as well as an in-built MIDI player.

- A grafical user interface for controlling the components.

The main component is the microtonal tuner which tunes all notes justly according to the present harmonic context. While other existing algorithms try to solve this problem mathematically by determining the chordal root of rational frequency ratios, our tuning algorithm is designed in such a way that it mimics what musicians do: A singer in a choir does of course not solve complicated puzzles with rational numbers, instead she/he adjusts the pitches intuitively in such a way that the best possible intonation is achieved. Our algorithm does exactly the same: It reduces the impurity (tempering) of the sound as much as possible.

How does this algorithm work? This can be explained most easily in the analogy of an electrical circuit. Suppose that a C-Major chord is being played (see figure). Let us associate with each pressed key an electric contact and let us connect all possible intervals by resistors and batteries with a voltage equal to the desired ideal pitch difference of just intonation in cents. In such a network the voltages at the contact will then adjust in such a way that they coincide exactly with the desired pitches of just intonation. However, for more complex chords which cannot be tuned justly, this algorithm automatically renders a reasonable compromise which approximates just intonation as much as possible.

Just Intonation – User Interface

Getting started

Just Intonation has been developed as a scalable multiplatform application, running on most devices ranging from desktop computers to mobile phones. Open the project website

www.just-intonation.org

and proceed to the download page, where the available platforms are listed. For desktop computers download the respective installer and follow the usual instructions. On mobile phones go to the respective App Store, where you can download *Just Intonation* as usual.

License

Just intonation is free software published under the GPLv3 license. This means that you are allowed install an arbitrary number of copies for private and commercial purposes. Using this software is at your own risk. The source code is public and everyone is invited to join the development of the project.
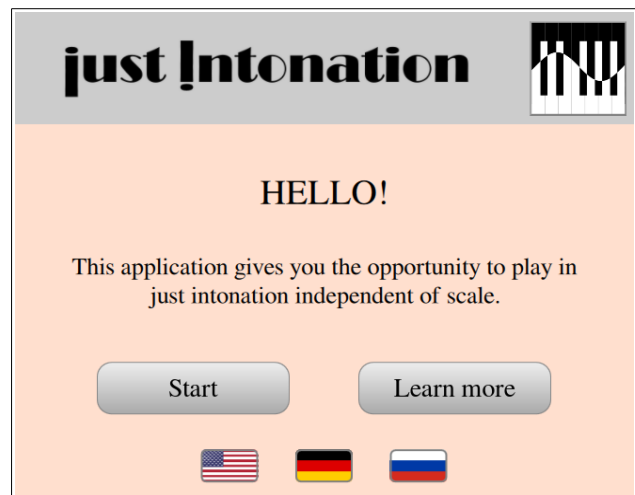
Download of samples

Starting the application you should see the welcome screen where you can select the language, start the program, or return via "Learn more" to the aforementioned website.

The application can reproduce the sounds of realistic instruments, including piano, organ, and harpsichord. The memory-consuming sound samples are not part of the application itself but have to be down-loade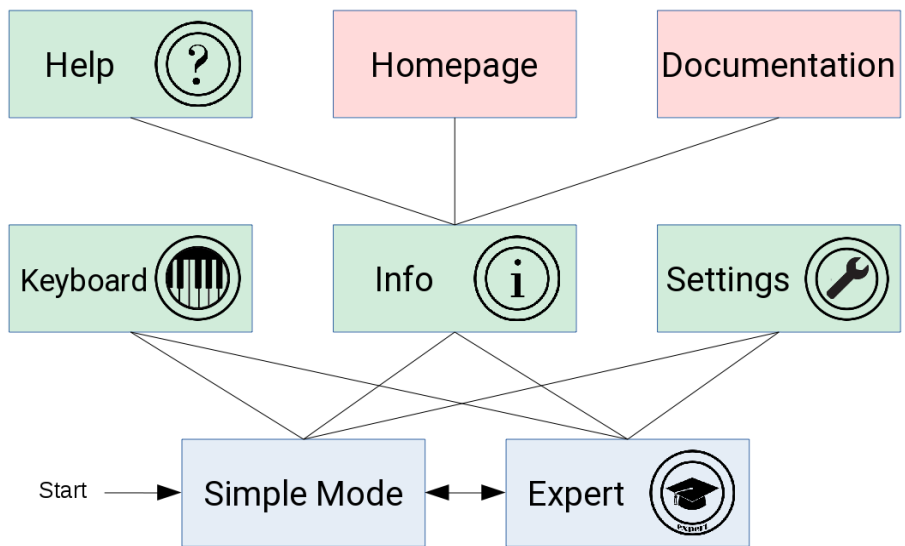d separately from our Web server. Starting the application for the first time you will be asked whether the application is allowed to download these files automatically in the background, which requires about 600 MB of permanent storage. We highly recommend to give the permission for download because otherwise the application can produce only very simple artificial electronic sounds.

Navigation Structure

The figure above shows the simple navigation structure of the application. After starting *Just Intonation* one is first led to the *Simple Mode*, a minimal user interface that will be
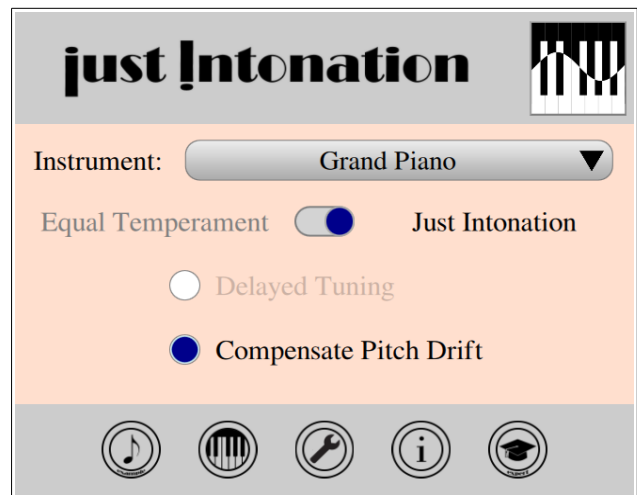
Navigation structure

described below. From there you can open the touchscreen keyboard, the help dialog, the settings dialog, or move to the *Expert Mode*. The Expert Mode offers a large variety of possibilities for modifying the tuning process and doing experiments with different temperaments.

For a more convenient navigation on devices with an alphanumeric keyboard the following keyboard shortcuts may be useful:

F1	Help selection panel
F9	Open system settings
E	Enter expert mode
K	Show keyboard on the screen
I	General information about the application
Return key	Toggle between ET and Just Intonation
Space bar	Midi player: toggle play/pause
Back/Delete	Reset pitch progression
⇐ ⇒	Previous / next MIDI example
⇑ ⇓	Adjust global concert pitch
ESC	Go back to the previous level

Simple Mode

The simple mode provides a minimal user interface that allows you to compare dynamically tuned just intonation and the standard equal temperament. In this mode the user can interact with the following components:

- **Download progress indicator**

    If the application is allowed to download samples from the internet, the actual download progress is shown as a horizontal bar (see below). Each instrument is downloaded separately, i.e., the progress bar runs from 0 to 100% several times. The total download time depends on the bandwidth of your internet connection, varying from a few minutes to one hour. The samples are downloaded silently in the background so that you can already use the application during the download.
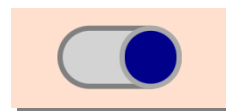

Download progress bar

- **Instrument selector**

    This combo box allows you to select the instrument. By default the application comes with artificially generated samples (triangular waves). If the application is allowed to download samples from the internet, the downloaded instruments (piano, organ, harpsichord) will appear as well. If these instruments do not appear the download is either still in progress or it may have failed. In this case try to reload the instruments from the setting dialog (see below).

    As of version 1.2, it is also possible to connect an external sound-generating Midi device such as an electronic piano or a synthesizer. In this case one has to select the last entry in the list (External Midi Output). See details on page 25.

- **Temperament switch**

  Tap this switch to toggle between just intonation and the equal temperament. All pitches are instantly changed so that you can immediately hear the difference between the two tuning schemes. If you have a keyboard you can also use the return key to toggle between the temperaments.

- **Delayed tuning**

  Checking this button the sampler will play each note for the first 1.5 seconds in the equal temperament before it switches to just intonation. This allows you to hear the difference between the equal temperament and just intonation without toggling the temperament switch. Delayed tuning is particularly useful if you play by yourself on a MIDI keyboard, but otherwise it should be turned off.

- **Pitch drift compensation**

  As outlined above, dynamical adaptive tuning schemes have the disadvantage that the global pitch may begin to migrate. Normally the application compensates this drift automatically. Uncheck this button in order to hear what happens if the automatic drift compensation is turned off.

- **Example button**

  The application comes with several in-built MIDI files[9] so that you can hear music out of the box. Tap this button to toggle between 'play' and 'pause'. If you want to play your own MIDI files simply drag the file from your file manager and drop it on the example button.

- **General help and information**

  Opens the help page with five different links for further information.

9   The included MIDI files are either in the public domain or protected by Creative Common licenses. To find out further details please go to the expert mode and press the "Info" button in the examples panel.

- **Touchscreen keyboard**

  If you do not have an external MIDI keyboard or if the necessary USB adapter is missing you can use the inbuilt touchscreen keyboard. This keyboard is particularly suitable for tablets. On desktop computers you can use the mouse to toggle individual keys (see below).

- **Preferences**

  This dialog allows you to modify the system settings such as the configuration of the MIDI device and the audio interface as well as other system–relevant parameters.

- **Expert mode**

  Opens the expert mode for advanced users, as will be described below.

Expert Mode

The expert mode has been designed for users who like to do their own experiments. Here the screen displays the following four panels:

- **MIDI player**

  The MIDI player is self-explaining and easy to use. To upload a MIDI file on a desktop computer press the upload button and choose a file with the extension *.mid. Alternatively you may simply drag the MIDI file from the file manager and drop it on the panel of the MIDI player.

- **MIDI examples**

  Browse in-built MIDI examples and learn more about the authors and the copyright by pressing the Info button.
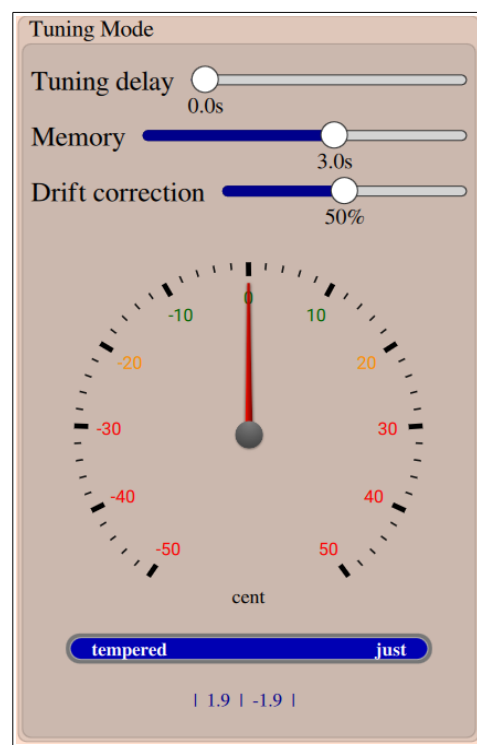
- **Instrument selector**

  This combo box allows you to choose the instrument in the same way as in the simple mode. In addition the concert pitch of A4 can be adjusted in the range from 400 Hz to 480 Hz. The pitch can also be adjusted with the arrow keys ↑↓.

- **Tuning mode**

  This panel controls the tuning parameters. On top there are three sliders. The first one controls the tuning delay which is useful to hear the difference between equal in just intonation if you play by yourself. The second slider determines the time scale on which subsequent harmonies will be correlated.

  As outlined above, non-equal temperaments have the side effect of a migrating average pitch due to the harmonic progression. The actual deviation of the average pitch is indicated by the circular gauge which spans the range of one semitone. The third slider controls the efficiency of the automatic pitch correction from 0% to 100%. Moving this slider to the left the drift compensation is turned off which allows the user to hear and see how the pitch differences accumulate with time.

  Below the circular gauge there is another linear indicator showing how much the tuning result is tempered. An entirely blue bar indicates that the present chord is tuned perfectly in just intonation. A partially filled red bar means that the chord is so complex that just intonation between all intervals is impossible. The gauge gives an idea how far the computed results differs from just intonation.[10]

  At the bottom below the linear gauge the panel shows numbers separated by vertical bars. These numbers are the interval sizes between neighboring keys of the currently playing chord measured in units of cents versus the ET.

- **Temperament selector**

  The panel on the right-hand side controls the temperament. The upper combo box allows you to choose between equal, just, meantone, and pythagorean intonation as well as an arbitrary user-defined temperament. The chosen temperament is tuned dynamically unless the checkbox right below (Static Tuning) is checked. In this case

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10 The linear gauge shows the value of the deviation potential exp[-V[λ]] at the optimal point, see our paper where the tuning method is described in detail.

the user has to specify the reference tone of the static temperament. For example, if we want to hear statically tuned just intonation in C major we would have to choose C. This option can be used to demonstrate why statically tuned just intonation does not work when it comes to scale changes.

Further below you will find the twelve intervals of the chromatic scale listed together with combo boxes for the respective cent deviations relative to the ET. In addition there are 12 sliders which quantify the acoustical importance of the interval. Being on the left side means that the interval is very elastic and flexible, adjusting its pitch in the harmonic context. On the other hand, if the slider is moved to the right, the interval is rigidly tuned to the defined pitch. In order to understand how this works in detail please refer to the respective documentation.

Temperament		
User-defined ▼		
○ Static Tuning		C ▼
Copy JI	Set ET	Reset

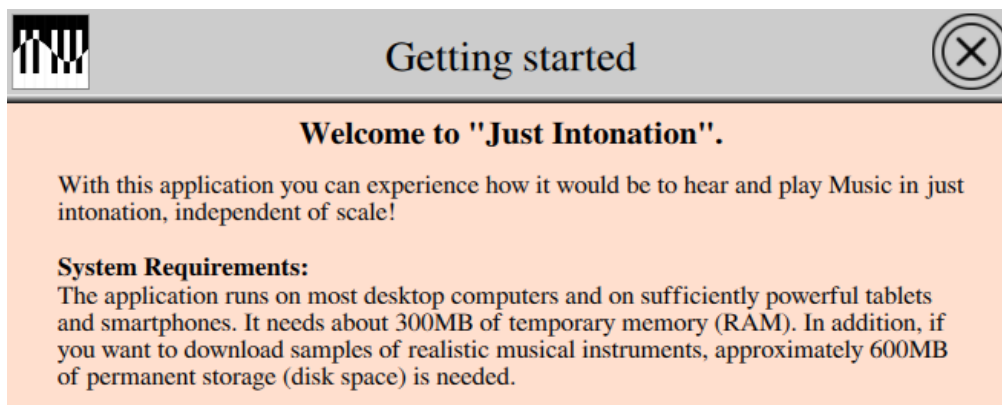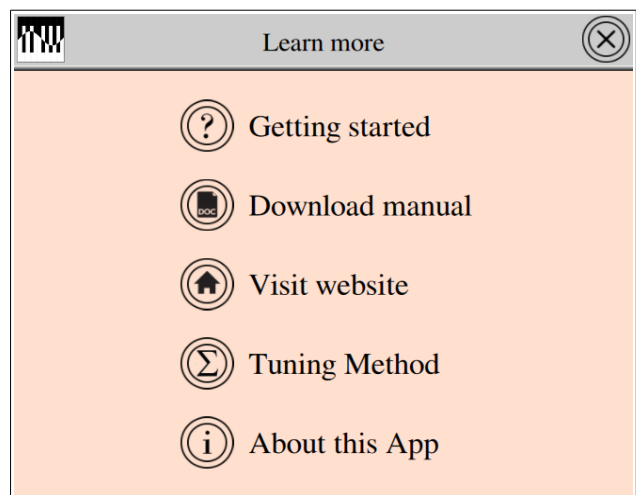| Interval:	Deviation:	Weight:
Semitone	11,73 ¢	
Major Second	3,91 ¢	
Minor Third	15,64 ¢	
Major Third	-13,69 ¢	
Perfect Fourth	-1,96 ¢	
Tritone	-9,77 ¢	
Perfect Fifth	1,96 ¢	
Minor Sixth	13,69 ¢	
Major Sixth	-15,64 ¢	
Minor Seventh	17,60 ¢	
Major Seventh	-11,73 ¢	
Octave	0,00 ¢	

Help and Information

The help dialog shows five options for further information. The first one is a short off-line summary for getting started. The second one leads to this manual while the third one is linked with the project homepage.

The fourth button leads you to a paper in which the tuning method is described in more detail (to appear in April 2017).
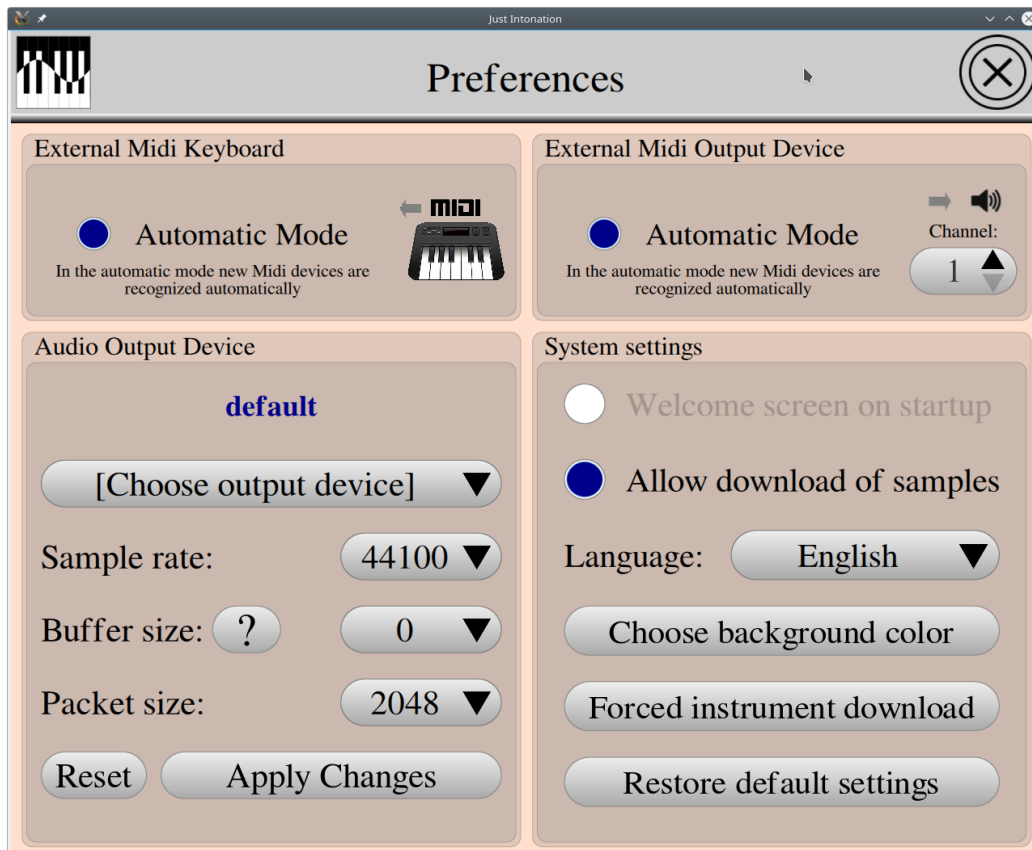
Finally, the last button opens the "About dialog" of the application, providing information about the version, license, the authors and other contributors.

The offline help dialog

Preferences Dialog

Here you can specify various preferences such as the MIDI interface configuration, the audio settings, and various system related settings. As a rule of the thumb, you should change these settings only in the case of problems.

- **External MIDI Keyboard / External MIDI Output Device**

    In the upper two panels it is possible to control the settings for MIDI input (left) and MIDI output (right). The MIDI input can be connected to any device that generates a stream of MIDI signals such as hardware keyboards or software sequencers. Likewise the MIDI output can be connected with any sound-generating MIDI device such as electronic pianos as well as hard- or software synthesizers. Note that the output device has to support so-called pitch-bend commands (see below).

    In both cases the easiest way is to operate in the "Automatic Mode", where the application automatically establishes a connection with the most recently connected MIDI device. If the automatic mode is deselected one can choose one of the devices
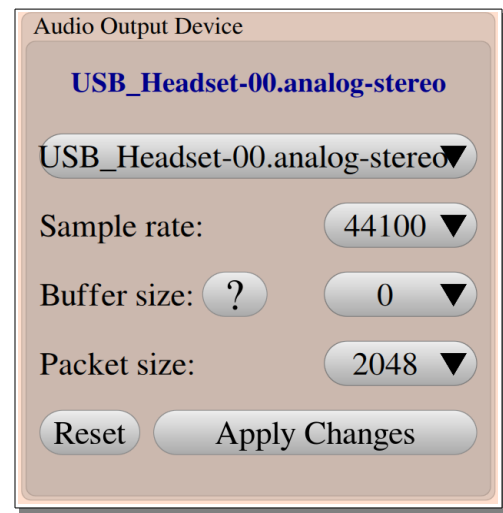
listed in the combo box below. The name of the actually connected MIDI device is shown in blue color at the top of the respective panel.

In the output mode one can also specify the number of the instrument according to the MIDI norm. This depends on the actual device, but in most cases '1' stands for a grand piano. Note that some computers provide inbuilt virtual MIDI devices such as "Midi through 14:0" or similar which have no active functionality.

- **Audio settings**

Note that in contrast to the other panels, changes in the audio settings will become effective only when pressing the button "Apply Changes". If you are not sure about the settings you can restore the standard values by pressing "Reset".

The name of the actually connected sound-card is shown at the top line in this field in blue color. Normally the application is automatically connected to the standard device (speaker or headphone). If you want to use a particular device such as Bluetooth speakers select the corresponding entry in the combo box. Note that Bluetooth devices may have a high latency.

Just Intonation works with a fixed sample rate of 44.100 Hz. Please do not change this value: you will hear everything in the wrong pitch!
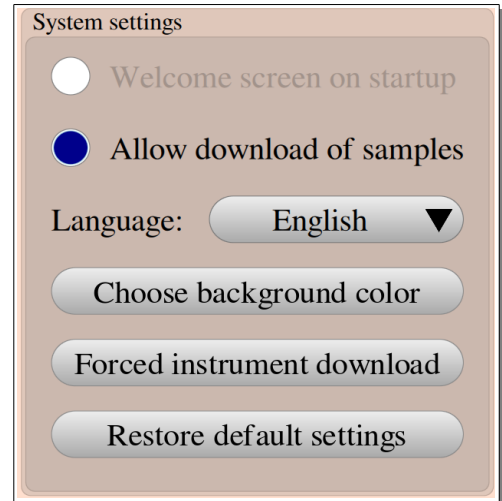
The last two entries, namely the buffer size in the packet size, should only be changed in the case of serious problems, for example, if you hear nothing or only corrupted fragments. To understand these parameters note that the audio stream generated by the application is not continuous, rather it is sent in small portions, called *packets*. These packets fill a buffer in the audio device which then streams the accumulated data in real time. This inevitable mechanism leads to a small delay, called latency. Moreover, in case of a buffer underflow the audio stream is inter-rupted, leading to an unpleasant intermittent sound. If you encounter such prob-lems you can try to play around with the parameters. The buffer size is this memory size of the soundcard, defining the latency, while the packet size is the size of the portions delivered by the application.
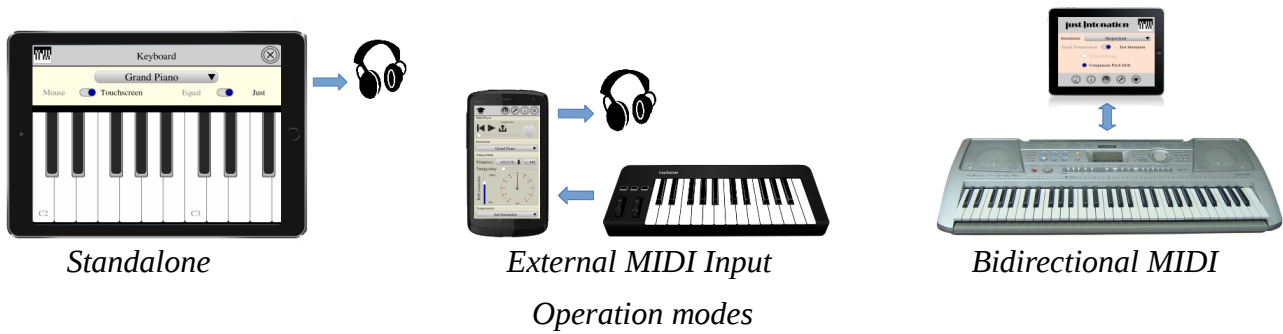
- **System–related settings**

  Here you can specify whether you would like to see the welcome screen on startup. In case that you denied Internet access you can revert this decision by clicking the respective checkbox. Right below you find the language selector. Changing the language will restart the application.

  Our development team could not agree on the background color. As a solution, we assigned a different background color for each day of the week. If you prefer your own favorite background color please choose it by clicking the respective button.

  If for some reason the application didn't load the instrument samples the download can be forced by tapping the respective button. Finally, if the application behaves irregularly, it is possible to restore the default settings.

System settings

⬤ Welcome screen on startup

🔵 Allow download of samples

Language: English ▼

Choose background color

Forced instrument download

Restore default settings

| *Standalone* | *External MIDI Input* | *Bidirectional MIDI* |

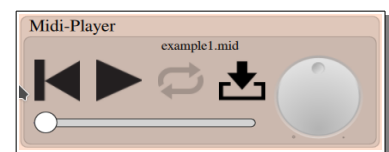*Operation modes*

Using the software

Listening to music

Listening to in-build examples

Just intonation comes with several inbuilt MIDI files. In order to hear these example files simply press the example button in the simple mode to toggle between play and pause. If you stop the example before it has ended the application automatically switches to the next example. The same functionality is provided by the MIDI player in the expert mode.

Loading and playing MIDI files

On a desktop computer MIDI files can be uploaded to the MIDI player by pressing the upload button or by dragging and dropping MIDI files (*.mid) on the example button or on the area of the MIDI player. The actual file name is shown in the upper line of the MIDI-player.

Press the play button to play the MIDI file. If you want to hear a short MIDI sequence repeatedly activate the "repeat" button. The rotary knob can be used to control the tempo.

On mobile devices open a file manager to locate the MIDI file and touch it. The device then suggests applications which can open the file, and hopefully you will find *Just Intonation* in the list.

Hearing the difference between ET and Just Intonation

To hear the difference between the equal temperament and just intonation simply toggle the intonation switch in the simple mode. On desktop computers you may also press the Enter key to toggle between the two modes.
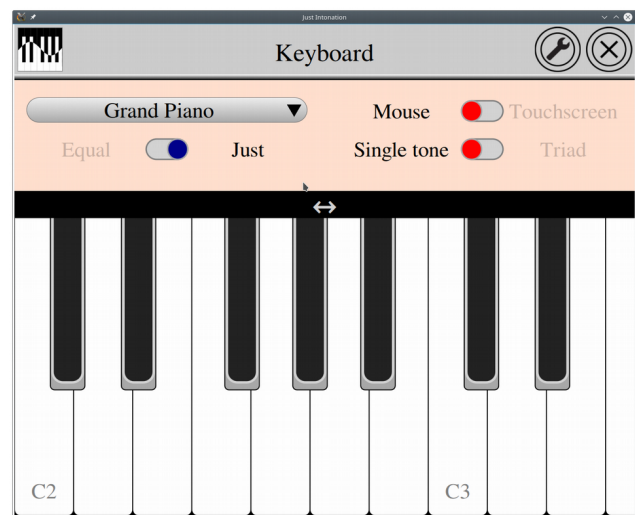
Start with a slow piece of music with simple chords or open the touchscreen keyboard (see below) and play chords by yourself. You will notice beats (interferences) in the equal temperament which are absent in just intonation. Be aware that some intervals like the fifth or the fourth show hardly any difference while intervals such as major thirds vary significantly.

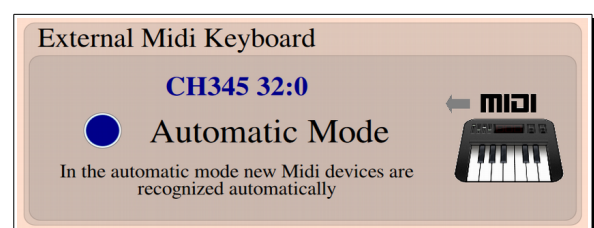# Playing music

Playing on the touchscreen keyboard

If you do not have a MIDI-keyboard at hand the application provides a simple in-built touchscreen keyboard. This option is particularly useful on tablet computers. Since the screen shows only a part of the whole claviature, the keyboard is "flickable", i.e., it can be moved to the left and to the right by a horizontal flick along the upper part of the keyboard.

You can choose between the "Mouse" mode, toggling the keys on and off by separate mouse clicks, and the "Touchscreen" mode. In addition, it is possible to generate a Major triad by pressing a single key. If you play such a triad you should toggle between equal temperament and just intonation in order to hear the difference.

Using an external MIDI keyboard

Although the touchscreen keyboard may be useful for a first test, it is much more convenient to connect an external USB keyboard. If the application is in the "Automatic Mode",

Just Intonation should recognize the keyboard automatically so that you can play immediately. The connection can be checked and modified in the preferences, where the name of the keyboard should appear in blue color (see figure). If the name of your keyboard does not appear you can also disable the automatic mode and choose the keyboard manually from the list of devices.[11]

USB MIDI keyboards can also be connected to various mobile devices. Android-based devices must have an "on the go" (OTG) USB connector and a special OTG adapter is needed. Similarly Apple iOS devices can be connected via a so-called "lightning to USB" adapter. Once connected, the operation system may ask you whether Just Intonation is allows to access the USB device.

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11 If the name of the keyboard does not appear at all this could be due to a problem of your hardware or the operating system. In this case would recommend to download other MIDI applications (e.g. software sequencers) and check under which conditions they are able to recognize the keyboard.
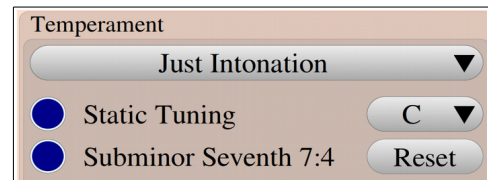
Experimenting with different intonations

Comparing static temperaments and dynamical tuning

As outlined above, just intonation as a static tuning scheme is impractical since it can only be used in its own reference scale while it is significantly out of tune in other scales. To demonstrate this active the option "Static Tuning" and specify the respective reference scale. For example, static just intonation with respect to C should be fine in C major but out of tune in virtually any other scale.
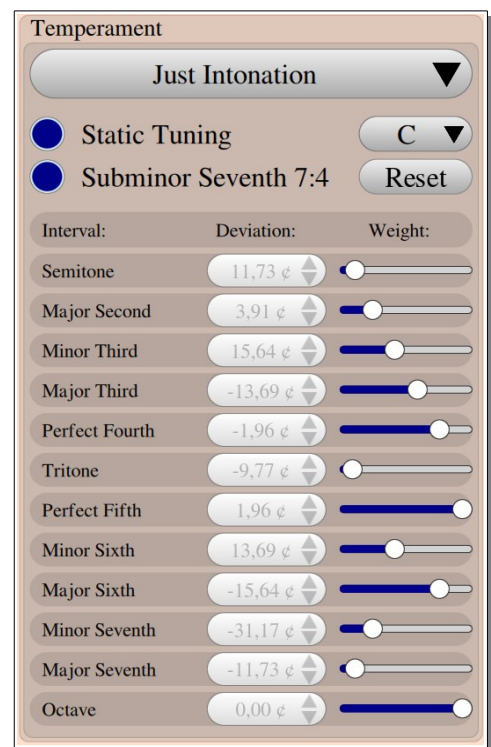
Comparing different temperaments

Just intonation and the equal temperament are the extremes in a whole spectrum of uncountable static temperaments that have been proposed in the past. The application includes the most important ones, namely Just Intonation, Pythagorean tuning, the ¼ meantone temperament, and the ET. All of them can be tested in the static as well as in the dynamically tuned mode. If you are interested in other temperaments choose the user-defined custom temperament and specify for each interval the cent values against the ET.

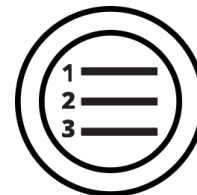## Investigating elasticity parameters

As outlined in the beginning, the tuning algorithm tempers intervals in complex situations where it is not clear how to construct coherent rational frequency ratios. In principle one could compute such compromises with equal weights for all intervals. However, the tolerance of the human sense of hearing with respect to tempering depends on the specific interval. For example, even small deviations of a fifth of fourth are perceived as unpleasant while deviations of the same amount in a second or seventh are hardly noticed. The algorithm exploits these differences in that it assigns different "elasticities" to the intervals. These elastic-

ities are controlled by the horizontal sliders in the figure above, preset to some reasonable but in principle arbitrary values. You may try what happens if one changes these elasticities. If you arrive at the conclusion that the default configuration should be a different one please let us know.
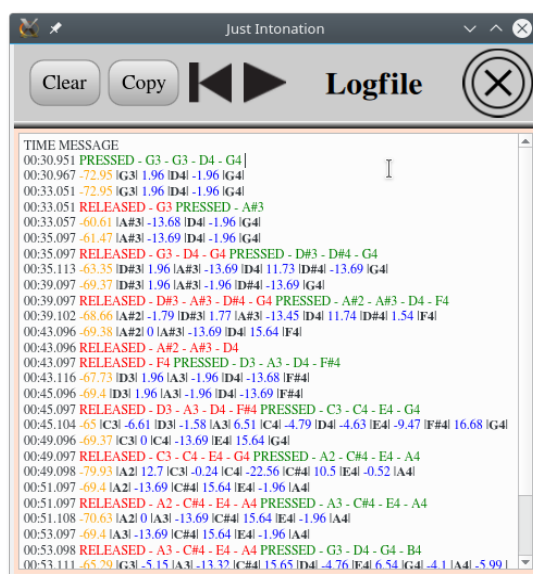
Analyzing interval sizes and pitch progression

For a quantitative analysis of the tuning procedure the application provides the possibility to monitor the tuning events in a log file. To see this file enter the expert mode and click the button shown right in the upper toolbar.

Then a window will open in which the tuning events are displayed while you are playing on the MIDI keyboard. Alternatively you can start the MIDI player in the upper toolbar and analyze the in-built MIDI examples or your own MIDI files.

There is no direct way to print the file but you can copy any part of the content to the clipboard, paste it to your favorite text processor, and print it from there. If you want to copy the whole file simply press the "copy" button in the upper toolbar.

A typical output looks like this:

> 00:30.951 PRESSED - G3 - D4 - G4
> 00:30.967 -72.95 |G3| 1.96 |D4| -1.96 |G4|
> 00:33.051 -72.95 |G3| 1.96 |D4| -1.96 |G4|
> 00:33.051 RELEASED - G3 PRESSED - A#3
> 00:33.057 -60.61 |A#3| -13.68 |D4| -1.96 |G4|
> 00:35.097 -61.47 |A#3| -13.69 |D4| -1.96 |G4|
> 00:35.097 RELEASED - G3 - D4 - G4 PRESSED - D#3 - D#4 - G4

Here the entries have the following meaning:

- Each line starts with the system time of the event in the format `min:sec.msec.`

- **Red** and **green** entries indicate changes of pressed and released keys.

- Between two messages about key changes the log file displays the first and the last tuning event. In between there are actually many more tuning events taking place

about every 20 ms. These intermediate event, in which the pitches are adjusted continually, are not shown in order to keep the log file readable.
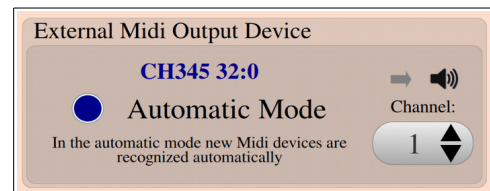
- Each tuning event begins with a number in orange color, indicating the **pitch of the lowest key** with respect to the ET at 440Hz, including both the global concert pitch and the actual harmonic progression. The black bold letters such as |**G3**| label the **currently audible keys**. Between these labels the log file displays in blue color the corresponding **interval sizes** in units of cents relative to the ET.

Connecting external sound-generating devices

As of version 1.2, it is now possible to play on external sound-generating MIDI devices in just intonation. This component of the software is still in a preliminary experimental state. Note that this feature will only work correctly on devices which understand so-called pitch-bend commands. If you encounter difficulties please let us know.

> **Background**: The MIDI norm, invented in back in 1982, was not designed for microtonal tuning of individual keys or notes. The only way to control the pitch is the so-called "pitch-bend" command, accessible for the user in form of a "pitch-bend wheel" of stage keyboards and synthesizers. The "pitch-bend" allows to tune a voice continuously, but only all keys together, preserving the ET. However, MIDI allows to play up to 15 voices in parallel, and each voice can be tuned separately. *Just Intonation* remaps the MIDI stream in such a way that each new note is assigned to a different voice (using the same instrument), which then can be tuned individually via pitch-bend. This trick allows the user to play on a conventional keyboard or synthesizer, provided that the device understand the necessary MIDI commands. The remapping, however, comes at the expense that only one instrument can be played with at most 15 tones at the same time, but for the purpose of this application this is not a serious restriction.

External devices could be hardware devices connected per USB such as electronic pianos, keyboards or synthesizers. Similarly it is possible to use software devices such as software synthesizers. As a major advantage, the latency in this operation mode is very small. However, the sound is now produced and controlled by the external device.

The device is most easily connected in the automatic mode, where *Just Intonation* connects itself to the most recently attached MIDI device. The name of the connected device is shown on top in blue color. If the name is not correct, uncheck the automatic mode and select the device by hand. In addition, one has to specify the number of the instrument according to the MIDI norm. Usually 0 and 1 stand for a piano.

To find out whether the device works properly go to the simple mode, select the instrument "External Device", and play one of the examples. The device should now receive the MIDI signals and play the music. Next go to the expert mode, vary the concert pitch, say from 440 Hz to 450 Hz, and listen whether the device goes up in pitch. If it does not the

device is unsuitable for playing in just intonation since it does not understand pitch-bend signals. Alternatively you may check the data sheet of your device to look up whether pitch bends are supported. Generally keyboards with a pitch-bend wheel are expected to work while more conservative electronic pianos without pitch-bend wheel are likely to fail.

If everything is all right you should proceed and compare simple chords in just intonation and the ET. There should be a clearly audible difference between the two temperaments.

Bidirectional mode

It is also possible to use an external keyboard not only for output but also for input at the same time. In everything works in an optimal way, you can simply connect your computer or cellphone via USB, select "External Device" as instrument, and play in just intonation on your keyboard out of the box.

Yamaha PSR-E443 with Android phone

Normally an electronic keyboards sends the information coming from the keys directly to its own sound-generating unit. To operate *Just Intonation* in the bidirectional mode it is necessary that this direct connection is disabled and all data take the detour via computer or smartphone. This requires that the keyboard understands the MIDI command "Local Control on/off". Otherwise you would hear an unpleasant interference of the ET sounds produced by the keyboard itself and the microtonally tuned sounds sent by the application.

Frequently asked questions (FAQ)

I can't hear a difference between just intonation and equal temperament

The ability to hear it the difference varies strongly from person-to-person. It also depends on the acoustic quality of your device. To hear the difference we recommend to use headphones in a silent environment. Note that intervals respond differently when switching from equal temperament to just intonation and back: fourths and fifths hardly change but thirds very strongly. Choosing the inbuilt artificial sound and playing a triad you should be able to hear the difference: in the ET the sound vibrates while in just intonation this sound is kind of static and clean. Then proceed with other instruments and try to hear the difference.

The instruments do not appear in the list

The combo box for instrument selection should show the entries "Artificial sounds", "Grand Piano", "Organ", "Harpsichord", and "External device". If some of the instruments are missing it means that the instruments could not be downloaded properly. Make sure that you have a fast internet connection (WLAN on mobiles), go to the settings dialog and press the button for reloading all instruments. This should fix the problem.

Upon keypress the sound appears only with a delay

The so-called latency depends on the audio driver and the operating system. Apple computers are known for a low latency while for Windows and Linux operating systems latency can be a serious problem. You may play around with the buffer size and the packet size parameters in the settings, but as we use the native audio interface, we do not have many options to improve the latency. However, it is possible to replace the standard audio drivers by more efficient ones, known as ASIO-drivers. If you have any suggestions please let us know.

Acknowledgements