The Opus Codec

High-quality, low-delay music codec

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Xiph.org

Xiph.org is a collection of open source, multimedia-related projects.[1]

1. Codecs: FLAC, Vorbis, Opus, Speex, Daala, Theora
2. Misc: RNNoise (**R**ecurrent **N**eural **N**[etwork])

The most aggressive effort works to put the foundation standards of Internet audio and video into the public domain, where all Internet standards belong.

1. Closed software and protocols are not evil or worse than open source, but by definition only exist serve the bottom line of a corporation
2. The Internet is built on open development, free exchange of ideas, and intellectual cooperation

[1] *Xiph.org: About*. URL: https://xiph.org/about/.

Why multimedia needs open standards

1. MPEG – **M**oving **P**ictures **E**xpert **G**roup – "is the name of a family of standards used for coding audio-visual information (e.g., movies, video, music) in a digital compressed format.[2]"
2. "Working group of ISO/IEC (**I**nternational **O**rganization for **S**tandardization, **I**nternational **E**lectrotechnical **C**ommission) in charge of the development of international standards for compression, decompression, processing, and coded representation of moving pictures, audio and their combination."
3. RIAA – **R**ecording **I**ndustry **A**ssociation of **A**merica –[3]

   We work to protect artists' creative freedom and promote the unique work that labels do to support them. [...] We work to protect artists and all music creators from the damaging impact of music theft.

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[2] *MPEG – The Moving Picture Experts Group*. URL: https://www.mpegstandards.org/.

[3] *What We Do – RIAA*. URL: https://www.riaa.com/what-we-do/.

MP3 in 1998

Fraunhofer/Thompson (two industrial giants holding MP3-related patents) started demanding royalties in 1998[4]:

> *Since 1997, we have been working with the MP3 source code released by the ISO. [...] Then we got an e-mail [...] "As you may know, both the Fraunhofer Institute and THOMSON have done important work to develop MPEG Layer-3 audio compression (before and after it became part of the MPEG standards). This work has resulted in many inventions and several patents, covering the MPEG Layer-3 standard. Our files do not show that you have a valid license agreement with us. This means that the products infringe the patent rights of Fraunhofer and THOMSON."*

RIAA sued an MP3 player manufacturer, Diamond, in the late 90s[5]

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[4] *What's New – Oct. 31, 1998*. URL: https://web.ncf.ca/aa571/wn103198.htm.

[5] Stephen W. Webb. "RIAA v. Diamond Multimedia Systems: The Recording Industry Attempts to Slow the MP3 Revolution, Taking Aim at the Jogger Friendly Diamond Rio". In: *7 RICH. J.L. & TECH. 5*. 2000. URL: https://core.ac.uk/download/pdf/232774502.pdf.

Containers and codecs

1. A *container* is associated to the file extension – it describes which codecs are used for its video/audio contents, followed by the actual encoded video/audio data, and extra data such as subtitles
2. A *codec* defines how to *encode* raw audio/video into data to put in a container (i.e. file), and how to *decode* data from the container back to a form suitable for playback[6]

File extension	Audio codec	Video codec	Container
.webm	Vorbis or Opus	VP8 or VP9	Matroska
.mkv	Any	Any	Matroska
.ogg	Vorbis	n/a	Ogg
.opus	Opus	n/a	Ogg
.mp4	AAC	MPEG-4	MP4

[6] Jean-François Fortin Tam. *Understanding codecs and containers*. URL: http://www.pitivi.org/manual/codecscontainers.html.

The Opus Codec

Audio codec designed for the Internet[7]

- Open-source, royalty-free
- Lossy
- Can trade off quality to reduce latency
- Derives from:
  - CELT (**C**onstrained-**Energy** and **L**apped **T**ransform)
  - SILK, Skype speech codec
- Replaces Vorbis (music) and Speex (speech) in a single codec

Opus can operate in three modes:

1. SILK mode for speech – low bitrate narrowband speech
2. CELT mode for music – high bitrate, high quality music
3. Hybrid – SILK <8kHz, CELT >8kHz

[7] Jean-Marc Valin et al. *High-Quality, Low-Delay Music Coding in the Opus Codec*. 2016. arXiv: 1602.04845 [cs.MM]. URL: https://arxiv.org/abs/1602.04845.

Speech and music

Sampling rate (Hz)	Max frequency (Hz)	Name
8000	4000	Narrowband
16000	8000	Wideband
44100	22050	CD
48000	24000	Fullband (DVD)

80% of perceptually important spectrum in *voiced* speech is <4kHz, however speech up to 8kHz is preferred in subjective tests (due to *unvoiced* speech)[8]. Humans can hear from 20Hz-20kHz, and music requires a larger frequency range than speech[9].

[8] Julien Epps and W.H. Holmes. "A new technique for wideband enhancement of coded narrowband speech". In: Feb. 1999, pp. 174–176. ISBN: 0-7803-5651-9. DOI: 10.1109/SCFT.1999.781522.

[9] Brian Moore. "Effects of Sound-Induced Hearing Loss and Hearing Aids on the Perception of Music". In: *Journal of the Audio Engineering Society* 64 (Mar. 2016), pp. 112–123. DOI: 10.17743/jaes.2015.0081.

Lossy compression and psychoacoustics

Lossy versus *lossless* encoding is the primary issue in data compression[10]
Lossy compression sacrifices data for space savings

A question of fidelity: can we perceive the lost data? In the case of audio encoding, we need to consider psychoacoustics and perception.

> *The basis of lossy psychoacoustical compression methods is the omission of information from the audio signal so that it does not result in perceived difference.*[11]

https://wiki.xiph.org/Opus_Recommended_Settings says to prefer FLAC (lossless) for archival to avoid generation loss[12]

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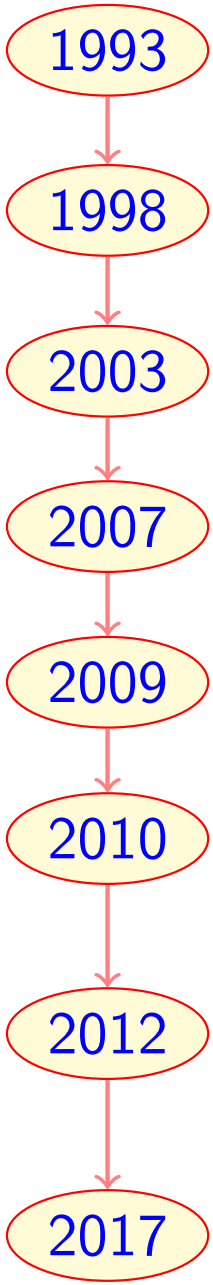
[10] Steven S. Skiena. *The Algorithm Design Manual*. London: Springer, 2008. DOI: 10.1007/978-1-84800-070-4.

[11] Péter Rucz. *Examination of lossy audio compression methods*. 2018. URL: https://last.hit.bme.hu/sites/default/files/documents/audio_labor_en.pdf.

[12] Frank Kurth. "An Audio Codec For Multiple Generations Compression Without Loss Of Perceptual Quality". In: (Aug. 2002).

Opus timeline



- Xiph starts on music codec Vorbis
- Vorbis development accelerated due to Fraunhofer Society MP3 royalties
- Xiph starts on speech codec Speex
- Xiph starts CELT starts as successor to Vorbis
- Skype opens SILK protocol
- Beginnings of Opus with hybrid CELT-SILK format
- Xiph gets Opus standardized in IETF https://tools.ietf.org/html/rfc6716
- Opus updated https://tools.ietf.org/html/rfc8251

Opus details – speech

The SILK half of Opus:[13]:

- *for speech, linear prediction techniques, such as Code-Excited Linear Prediction (CELP), code low frequencies more efficiently than transform (e.g., MDCT) domain techniques*
- Based on LPC (**L**inear **P**redictive **C**oding). Larynx emits simple signal (white noise or impulse train) through the articulatory system (throat, etc.) with coefficients. Sender sends articulatory coefficients, receiver recreates original sound by driving larynx signal through it[14]
- Computes LPC coefficients for *voiced* and *unvoiced* speech differently, using results of pitch analysis

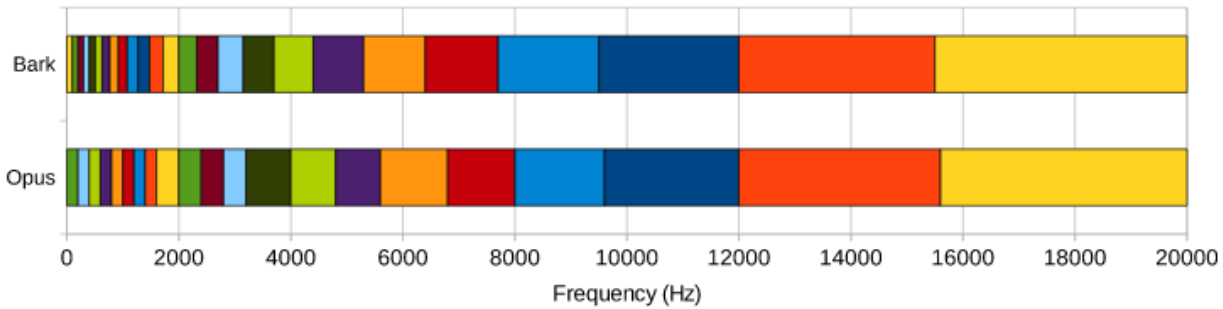
[13] K. Vos et al. "Voice coding with opus". In: *135th Audio Engineering Society Convention 2013* (Jan. 2013), pp. 722–731. URL: https://jmvalin.ca/papers/aes135_opus_silk.pdf.

[14] Shahram Shirani. "Speech Compression". In: *ELEC 728, McMaster University Department of Electrical Engineering* (2010). URL: https://www.ece.mcmaster.ca/~shirani/multi10/speech%20compression.pdf.

Opus details – music

The CELT half of Opus:[15]:

- Based on MDCT (**M**odified **D**iscrete **C**osine **T**transform). The DFT (**D**iscrete **F**ourier **T**ransform) decomposes a real acoustic signal into a sum of complex exponentials. The DCT uses only real cosines, and spectral energy is concentrated in fewer coefficients than the DFT[16].
- In addition to MDCT coefficients, CELT includes information about the spectral envelope of the signal with energy in Bark-like bands:

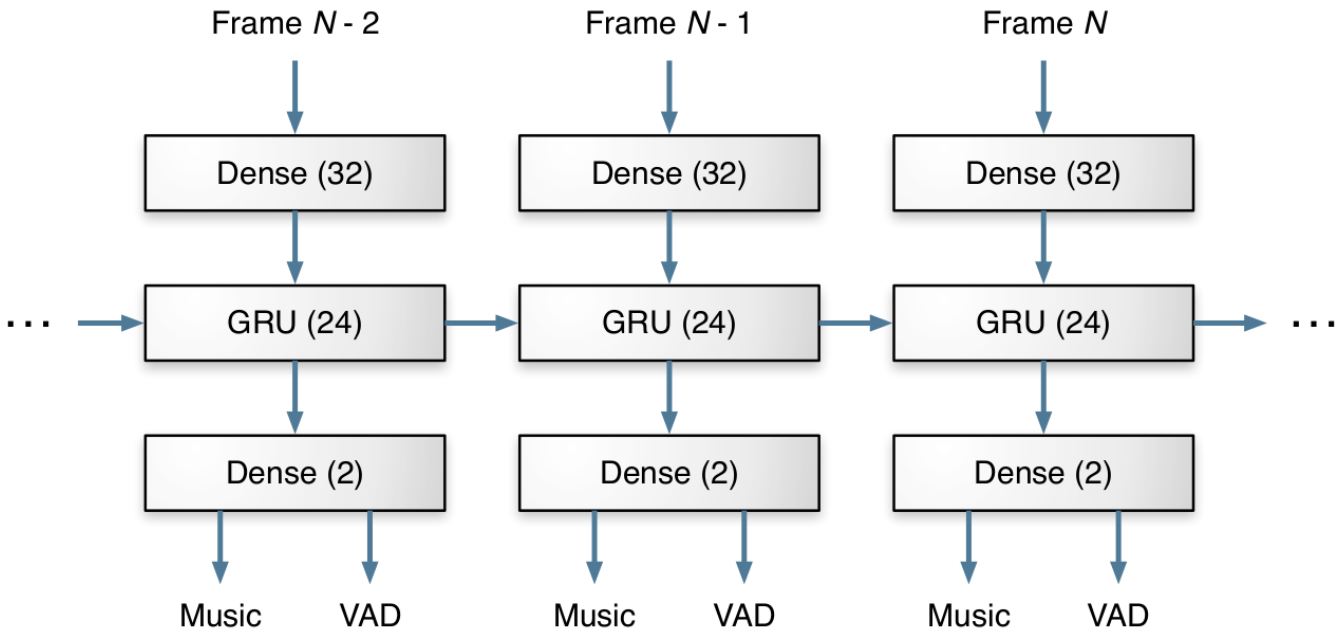


[15] Jean-Marc Valin et al. *High-Quality, Low-Delay Music Coding in the Opus Codec*. 2016. arXiv: 1602.04845 [cs.MM]. URL: https://arxiv.org/abs/1602.04845.

[16] N. Ahmed, T. Natarajan, and K. R. Rao. "Discrete Cosine Transform". In: *IEEE Transactions on Computers* (1974). DOI: 10.1109/T-C.1974.223784. URL: https://www.ic.tu-berlin.de/fileadmin/fg121/Source-Coding_WS12/selected-readings/Ahmed_et_al._1974.pdf.

Auto-detect music and speech

Opus can automatically detect whether its input is speech or music, and choose the optimal encoding mode accordingly. GRU (**G**ated **R**ecurrent **U**nit) with just 4986 weights (that fit in less than 5 kB) and takes about 0.02% CPU to run in real-time[17]



[17] Jean-Marc Valin. *Opus 1.3 Released*. URL: https://jmvalin.ca/opus/opus-1.3/.

Ambisonics, spatial audio

> *Opus 1.3 adds support for immersive audio using ambisonics that surrounds the listener in a full-sphere sound field. This is done through two new (soon to be RFC 8486) Ogg mapping families for Opus ambisonics. Unlike other multi-channel surround formats, ambisonics is independent of speaker layout. This allows for flexible speaker configurations and scalable audio to efficiently transmit 3D audio soundtracks.*[18]

https://tools.ietf.org/html/rfc8486

[18] Jean-Marc Valin. *Opus 1.3 Released*. URL: https://jmvalin.ca/opus/opus-1.3/.

Sound samples

https://opus-codec.org/examples/