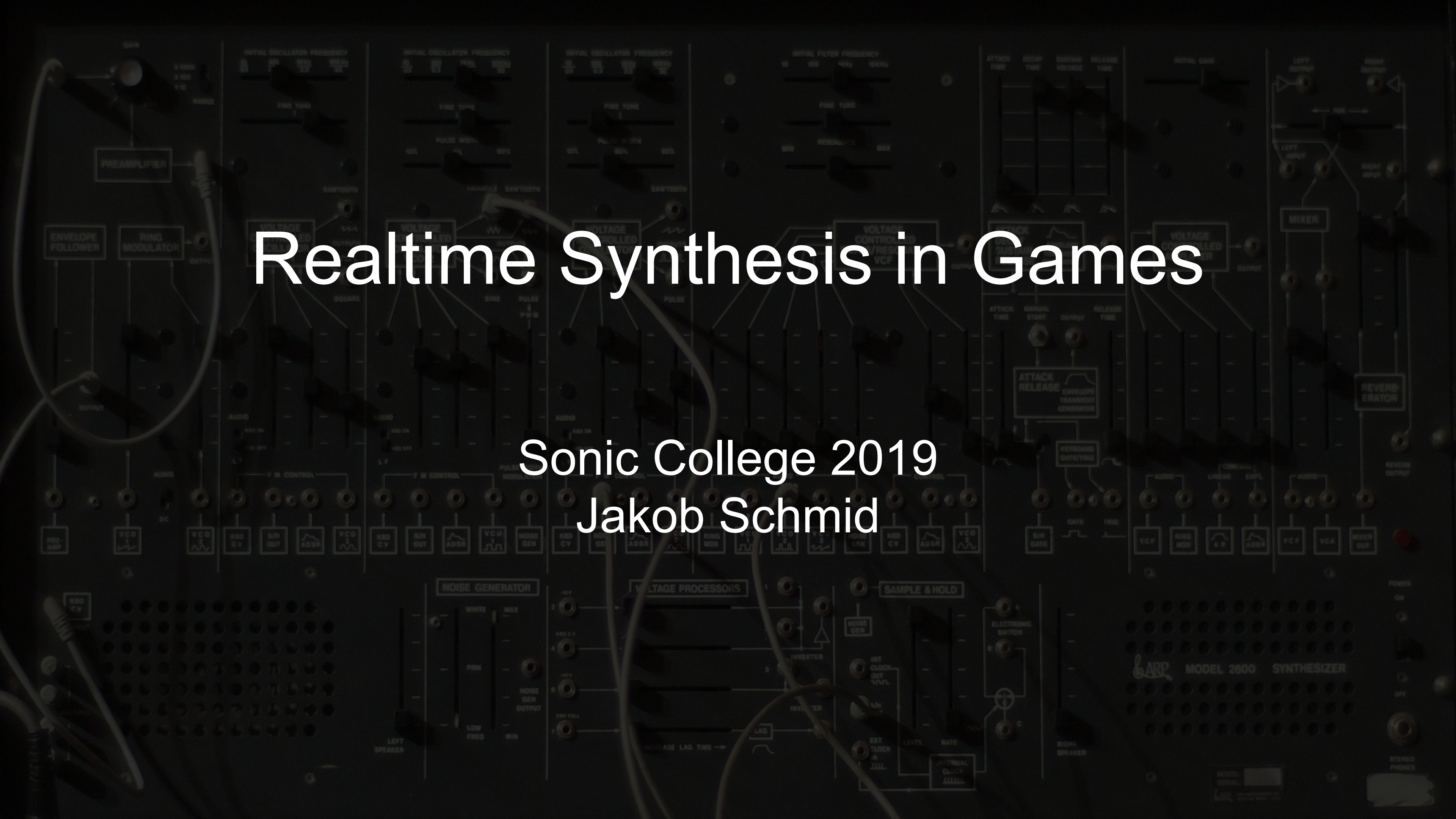


Realtime Synthesis in Games

Sonic College 2019
Jakob Schmid

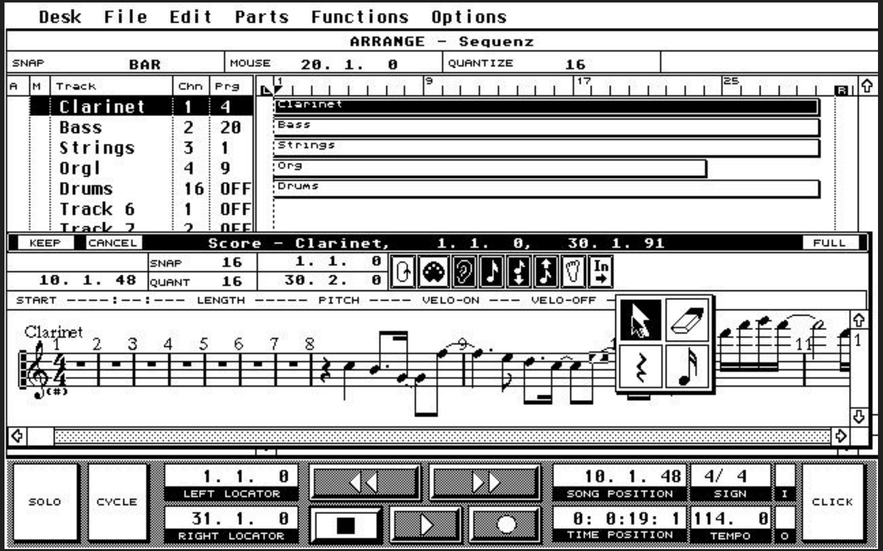
Overview

- Purpose and History of Realtime Synthesis in Games
- Dynamic Music in Games
- Audio Plugins
- Plugin Platforms
- Example Unity Plugins

Purpose of Realtime Synthesis in Games

MIDI-like Sequencing

- Sequencing of samples or real-time synthesis
- Key changes
- Removing notes
- Procedural / generative music



ARRANGE – Sequenz

SNAP BAR MOUSE 20. 1. 0 QUANTIZE 16

A	M	Track	Chn	Prg
		Clarinet	1	4
		Bass	2	20
		Strings	3	1
		Orgl	4	9
		Drums	16	OFF
		Track 6	1	OFF
		Track 7	2	OFF

Score – Clarinet, 1. 1. 0, 30. 1. 91

10. 1. 48 SNAP 16 QUANT 16 1. 1. 0 30. 2. 0

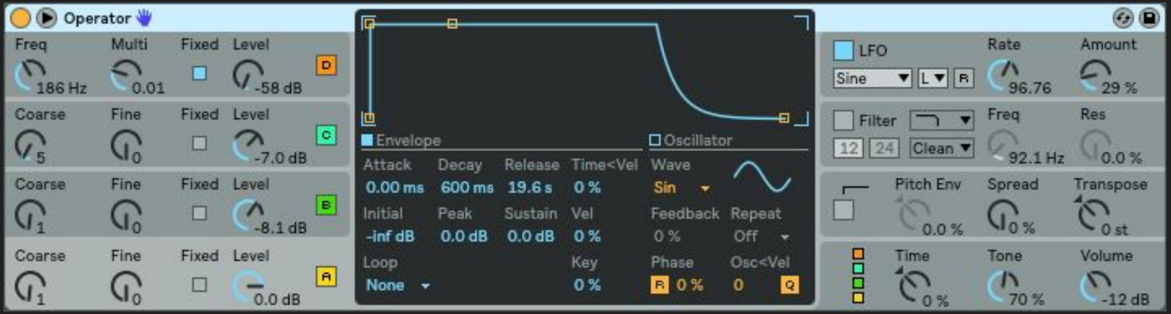
START ----:--:--- LENGTH ----- PITCH ---- VELO-ON --- VELO-OFF

1. 1. 0 LEFT LOCATOR
31. 1. 0 RIGHT LOCATOR
10. 1. 48 SONG POSITION
4/ 4 SIGN
0: 0:19: 1 TIME POSITION
114. 0 TEMPO

Cubase (1989)

Real-time Synthesis

- Parameter changes controlled from game
- Subtle changes in timbre accompany game events
- Variations in timbre retain player interest even though sequence repeats



Operator

D: Freq 186 Hz, Multi 0.01, Fixed ☑, Level -58 dB
C: Coarse 5, Fine 0, Fixed □, Level -7.0 dB
B: Coarse 1, Fine 0, Fixed □, Level -8.1 dB
A: Coarse 1, Fine 0, Fixed □, Level 0.0 dB

Envelope
Attack 0.00 ms, Decay 600 ms, Release 19.6 s, Time<Vel 0 %
Initial -inf dB, Peak 0.0 dB, Sustain 0.0 dB, Vel 0 %
Loop None, Key 0 %

Oscillator
Wave Sin
Feedback 0 %, Repeat Off
Phase R 0 %, Osc<Vel 0 Q

LFO ☑ Sine L R, Rate 96.76, Amount 29 %
Filter □ 12 24 Clean, Freq 92.1 Hz, Res 0.0 %
Pitch Env 0.0 %, Spread 0 %, Transpose 0 st
Time 0 %, Tone 70 %, Volume -12 dB

Ableton Live 10: Operator

History of Realtime Synthesis in Games

Realtime Synthesis was the Norm

- 1970s to mid 1980s: hardware-based realtime synthesis
- Hardware synthesizer-based hardware platforms
  - Arcade machines (1970s and forward)
  - Atari 2600 (1979)
  - ZX Spectrum (1982)
  - Commodore 64 (1982)

Marble Madness

ZX Spectrum

Commodore 64

Atari 2600

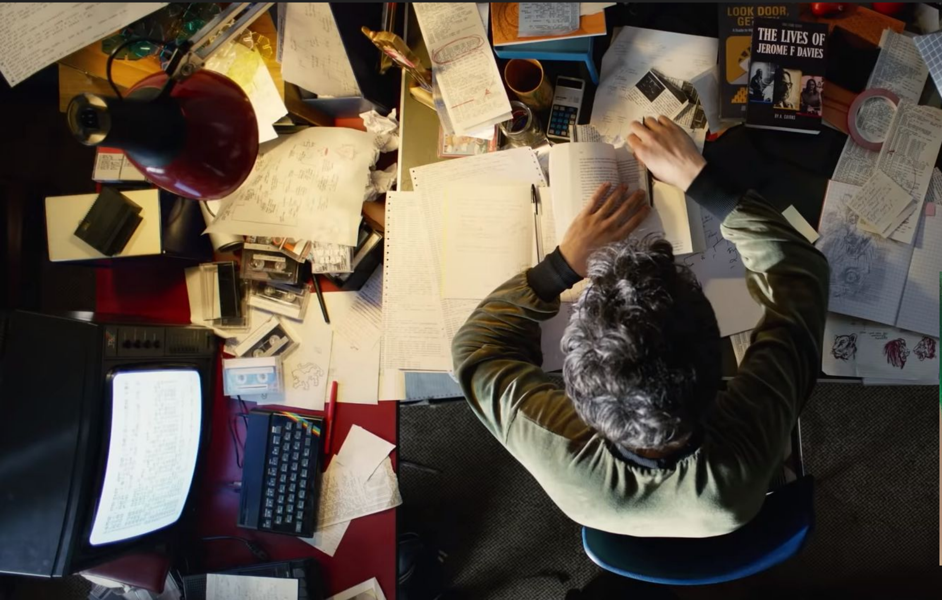
Real-time Synthesis was the Norm

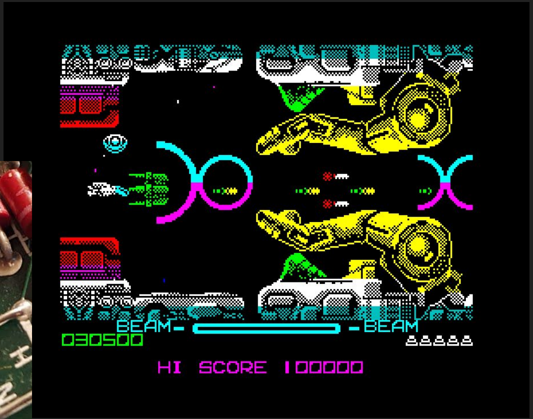
- Sound chips with fixed number of DCOs controlled from CPU
- Possible to play samples using clever tricks
- Sample playback hardware become the norm in 1985 and forward

Amiga 1000 (1985),
sample-based audio hardware

ZX Spectrum Speaker

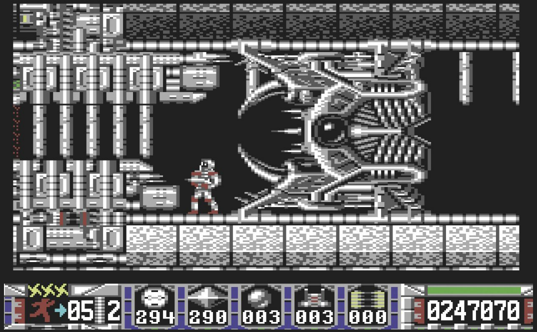
- 1 tone generator
- 1-bit volume, on or off





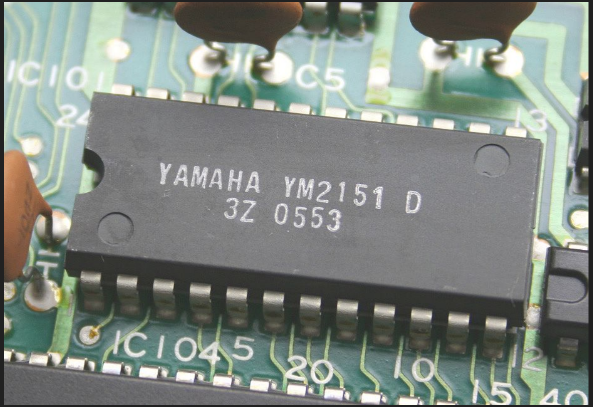
Commodore 64 SID Chip

- 3 DCOs
- Waveforms: pulse, triangle, saw, noise
- Ring modulation, oscillator sync
- Multimode filter: low-, high-, bandpass (6dB/12dB rolloff)
- 3 Envelope generators



Yamaha YM2151

- FM 4-operator synthesis
- 8 channel polyphony
- Used in many arcade games by Atari, SEGA, and Konami
- See also https://vgmrips.net/packs/chip/ym2151



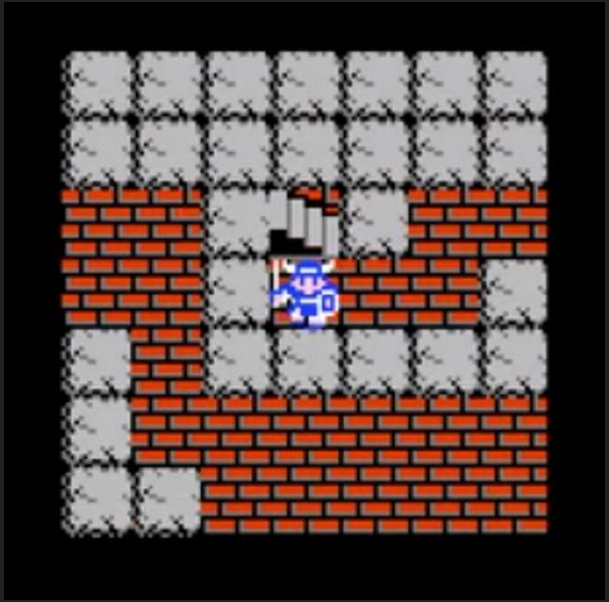
Summary

- MIDI-like sequencing allows generating or modifying notes
- Realtime synthesis allows for game-controlled parameter changes
- Hardware based realtime synthesis was the norm until mid 1980s
- Early audio hardware ranged from 1-bit tone generators to subtractive synthesis and FM synthesis.

Dynamic Music in Games

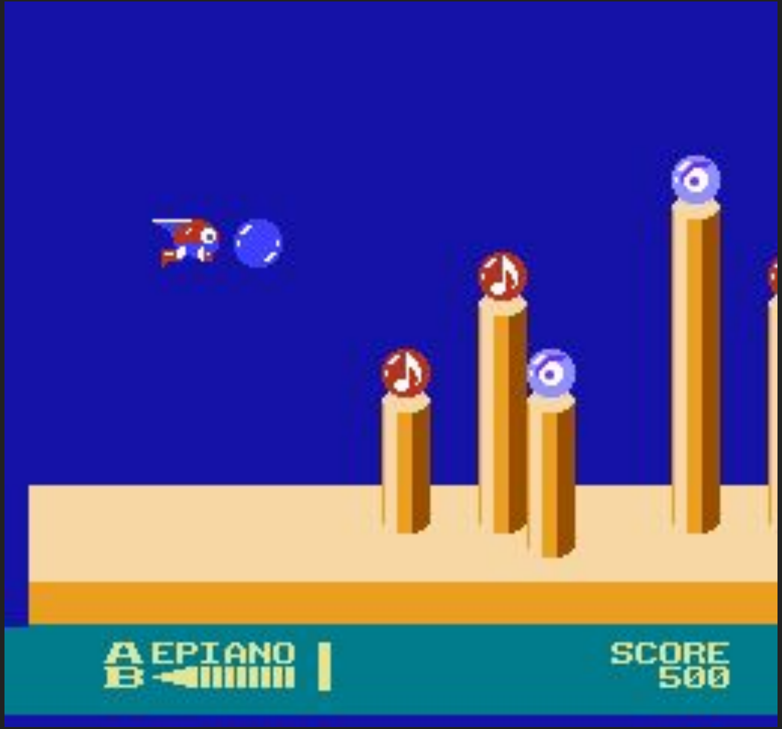
Dragon Warrior

- NES 1986
- Dungeon music changes key with dungeon level, assisting in finding your way around



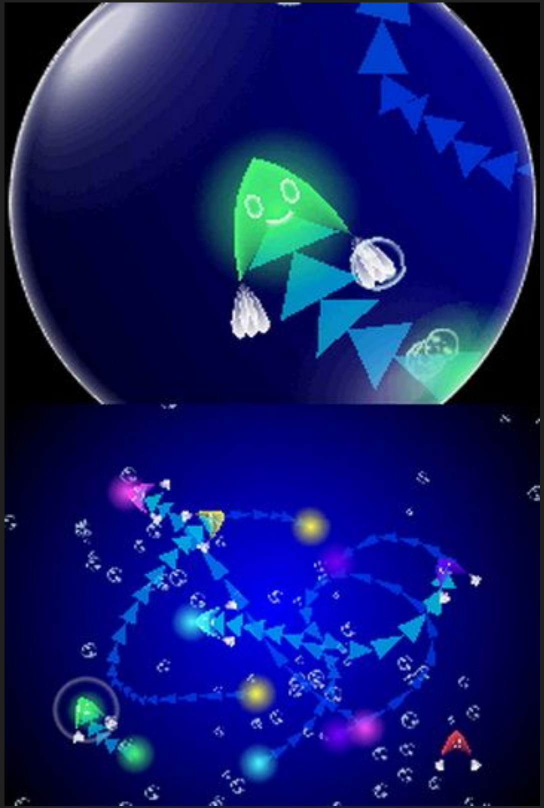
Otocky

- NES 1987
- Score is fully generated by gameplay elements



Electroplankton

- NDS 2005
- Generative music toy

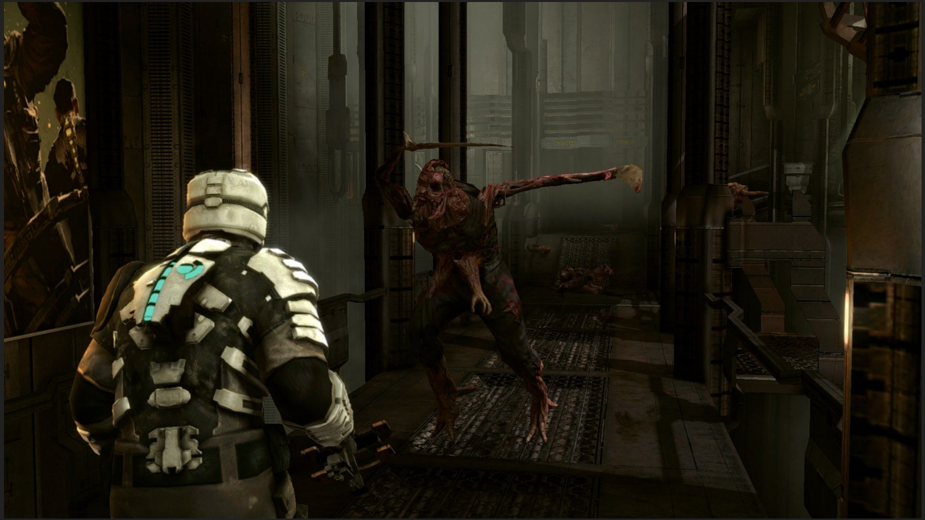


Spore

- PC 2008
- Generative score by Brian Eno
- Uses Pure Data

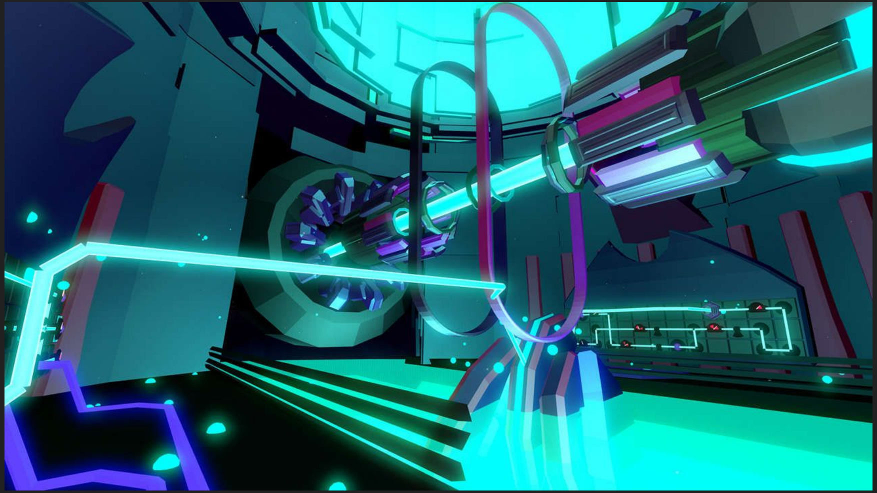
Dead Space

- Xbox 360, PS3 2008
- Uses traditional dynamic orchestral music
- Atonal orchestral stings are triggered by the player seeing a mutant for the first time



FRACT OSC

- PC 2014
- First-person puzzle game where you construct a realtime-synthesized piece of music
- Uses Pure Data

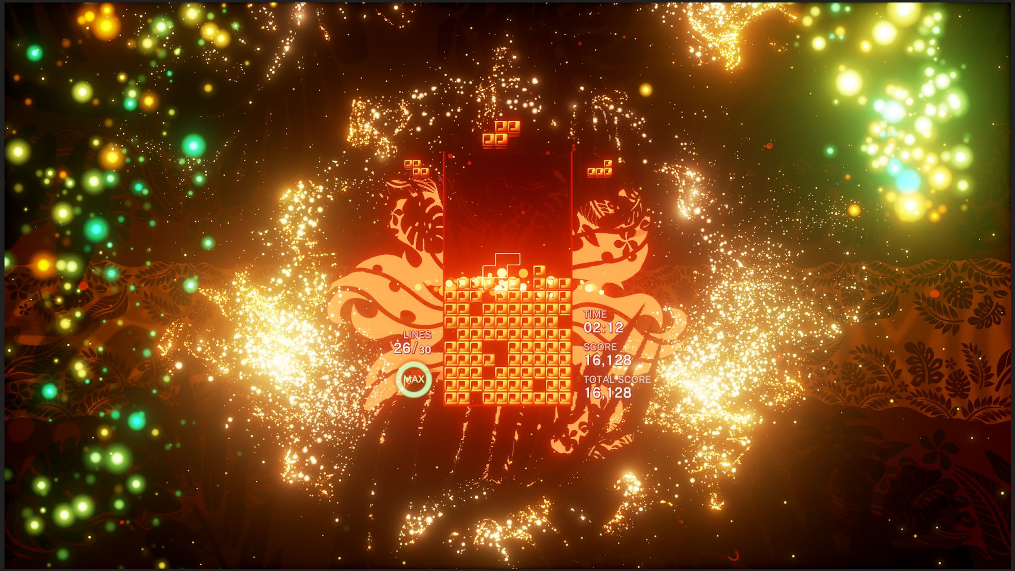


Rise of the Tomb Raider

- PS4, Xbox One 2015
- Dynamic Percussion System for battle sequences
- Generated drum sequence that reacts to battle intensity level

Tetris Effect

- PS4, Xbox One 2018
- Quantizes player input to beats and triggers samples in time with music
- Samples are pitched to reflect key changes in music



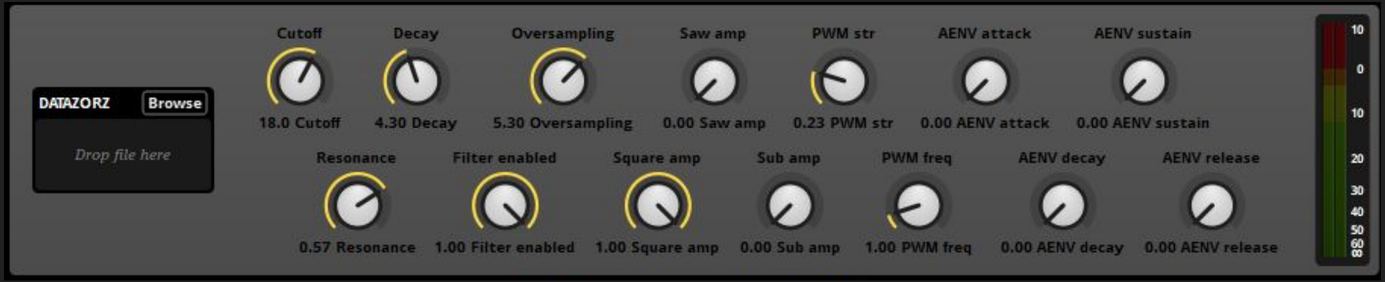
Summary

- Games have had dynamic music since 1980s
- Several games generate music via Pure Data
- Dynamic sequencing create variation and expresses game state
- Games can use player input as sequencing input

Audio Plugins

Modern Realtime Synthesis

- Implemented as audio plugins in sound engines
- Normally rendered on CPU, not in dedicated hardware

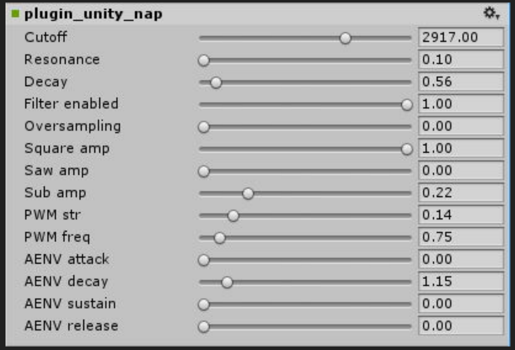


18.0 Cutoff
4.30 Decay
5.30 Oversampling
0.00 Saw amp
0.23 PWM str
0.00 AENV attack
0.00 AENV sustain
0.57 Resonance
1.00 Filter enabled
1.00 Square amp
0.00 Sub amp
1.00 PWM freq
0.00 AENV decay
0.00 AENV release

FMOD Studio plugin

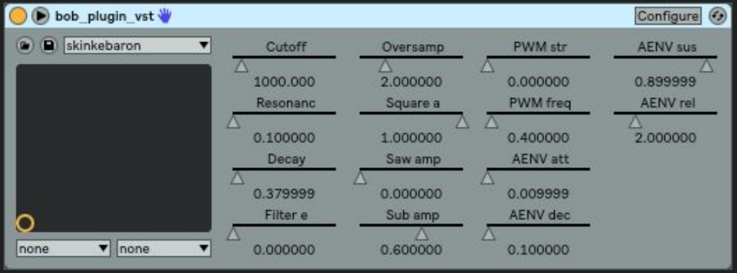
Audio Plugin Types

- FMOD Studio Plugin
- Wwise Sound Engine Effect Plugin
- Unity Native Audio Plugin
- VST 2.4
- Audio Units (Core Audio)



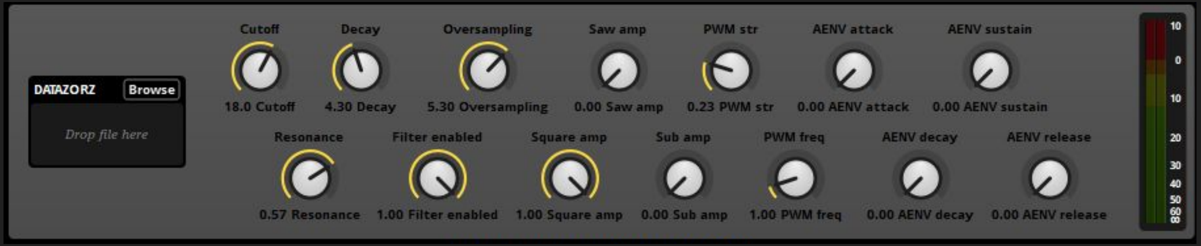
plugin_unity_nap

Cutoff	2917.00
Resonance	0.10
Decay	0.56
Filter enabled	1.00
Oversampling	0.00
Square amp	1.00
Saw amp	0.00
Sub amp	0.22
PWM str	0.14
PWM freq	0.75
AENV attack	0.00
AENV decay	1.15
AENV sustain	0.00
AENV release	0.00



bob_plugin_vst

Cutoff	1000.000
Resonanc	0.100000
Decay	0.379999
Filter e	0.000000
Oversamp	2.000000
Square a	1.000000
Saw amp	0.000000
Sub amp	0.600000
PWM str	0.000000
PWM freq	0.400000
AENV att	0.009999
AENV dec	0.100000
AENV sus	0.899999
AENV rel	2.000000



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0.00 AENV sustain
0.57 Resonance
1.00 Filter enabled
1.00 Square amp
0.00 Sub amp
1.00 PWM freq
0.00 AENV decay
0.00 AENV release

What is an Audio Plugin?

- A piece of code that outputs samples to an audio buffer
- Some wrapping that enables parameters and stuff

Audio Buffers

An audio buffer is a block of memory containing samples:

```
S0 S1 S2 S3 S4 S5 S6 S7
```

Rendering to Audio Buffer

An audio buffer is a block of memory containing samples:

```
buffer -> S0 S1 S2 S3 S4 S5 S6 S7
float [] buffer = new float[SAMPLE_COUNT];
```

Rendering code fills buffer with samples:

```
void process(float [] output, int length)
{
    for(int s = 0; s < length; ++s)
        output[s] = COMPUTE SAMPLE;
}
```

Stereo Audio Buffer

An interleaved stereo audio buffer:

```
L0 R0 L1 R1 L2 R2 L3 R3
```

Rendering to Stereo Audio Buffer

An interleaved stereo audio buffer:

```
L0 R0 L1 R1 L2 R2 L3 R3
```

Rendering code:

```
float [] buf = new float[SAMPLE_COUNT * 2];
void process(float [] output, int length) {
    int idx = 0;
    for(int s = 0; s < length; ++s) {
        output[idx++] = COMPUTE LEFT SAMPLE;
        output[idx++] = COMPUTE RIGHT SAMPLE;
    }
}
```

Synths vs. Effects

Implemented exactly the same way, except:

- Effects receive audio input
- Synths receive note and parameter input

Effect Rendering

Example code for a mono effect:

```
float [] input  = new float[SAMPLE_COUNT];
float [] output = new float[SAMPLE_COUNT];

void process(float [] input, float [] output, int length)
{
    for(int s = 0; s < length; ++s)
        output[s] = COMPUTE SAMPLE FROM input[s];
}
```

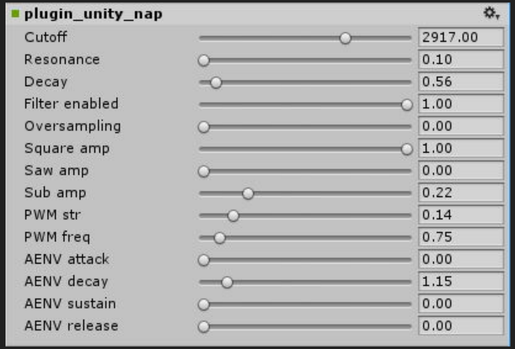
Summary

- Realtime synthesis is done using software audio plugins
- Different audio software have different plugin types
- Audio plugins output samples to audio buffer
- Synths and effects are very similar, except for their input

Plugin Platforms

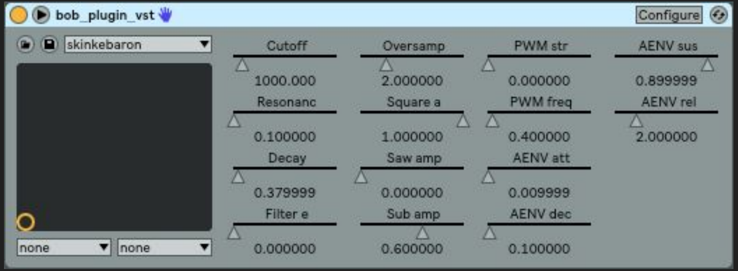
Plugin Platforms

Same code,
different
platforms



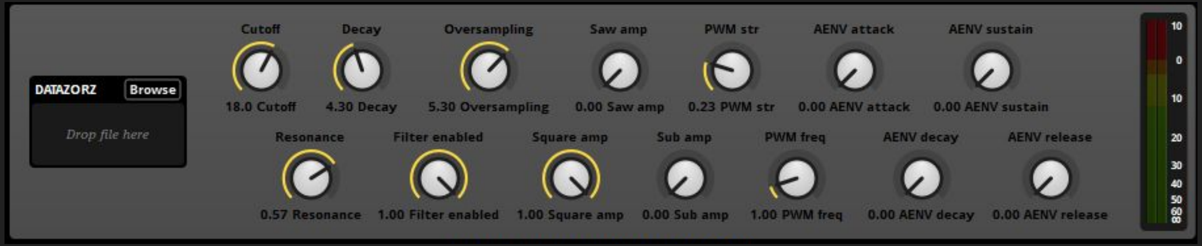
plugin_unity_nap

Cutoff 2917.00
Resonance 0.10
Decay 0.56
Filter enabled 1.00
Oversampling 0.00
Square amp 1.00
Saw amp 0.00
Sub amp 0.22
PWM str 0.14
PWM freq 0.75
AENV attack 0.00
AENV decay 1.15
AENV sustain 0.00
AENV release 0.00



bob_plugin_vst

Cutoff 1000.000
Resonanc 0.100000
Decay 0.379999
Filter e 0.000000
Oversamp 2.000000
Square a 1.000000
Saw amp 0.000000
Sub amp 0.600000
PWM str 0.000000
PWM freq 0.400000
AENV att 0.009999
AENV dec 0.100000
AENV sus 0.899999
AENV rel 2.000000



18.0 Cutoff
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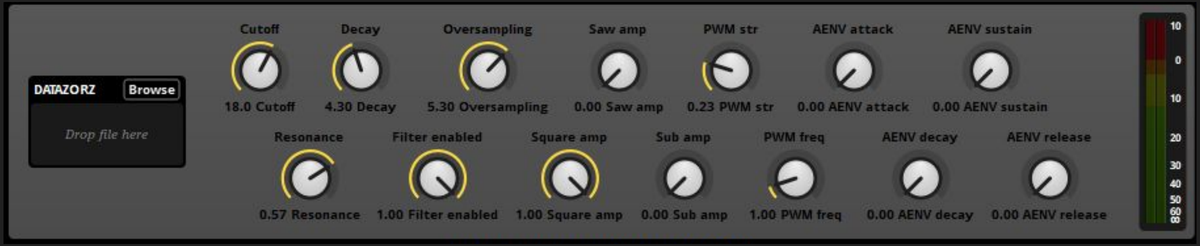
0.57 Resonance
1.00 Filter enabled
1.00 Square amp
0.00 Sub amp
1.00 PWM freq
0.00 AENV decay
0.00 AENV release

FMOD Studio Plugin

```
FMOD_RESULT F_CALLBACK Plugin_FMOD_dspprocess(
     FMOD_DSP_STATE *dsp,
     unsigned int length,
     const FMOD_DSP_BUFFER_ARRAY * inbufferarray,
           FMOD_DSP_BUFFER_ARRAY *outbufferarray,
            [..] )
     {
         RENDER length SAMPLES TO outbufferarray->buffers[0]
         return FMOD_OK;
     }
```



18.0 Cutoff
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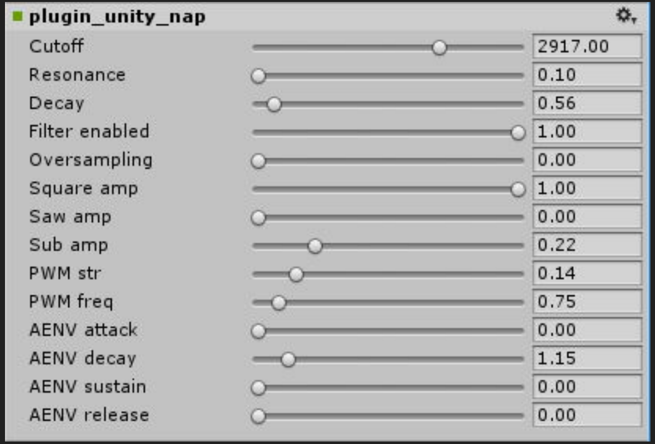
0.00 Sub amp
1.00 PWM freq
0.00 AENV decay
0.00 AENV release

Unity Native Audio Plugin

```
[..] ProcessCallback([..],
     float* inbuffer, float* outbuffer, unsigned int length,
     int inchannels, int outchannels)
     {
          RENDER length SAMPLES TO outbuffer
     }
```



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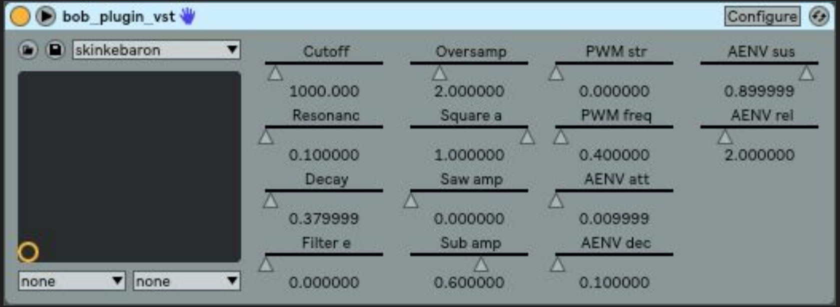
Decay	0.56
Filter enabled	1.00
Oversampling	0.00
Square amp	1.00
Saw amp	0.00
Sub amp	0.22
PWM str	0.14
PWM freq	0.75
AENV attack	0.00
AENV decay	1.15
AENV sustain	0.00
AENV release	0.00

VST 2.4

```
void VstXSynth::processReplacing(
     float** inputs, float** outputs,  // input / output - buffers
     VstInt32 sample_frames )          // buffer size
{
     // not interleaved, left and right are separate
     float* buf_left  = outputs[0];
     float* buf_right = outputs[1];
     RENDER sample_frames SAMPLES TO buf_left AND buf_right
}
```



Cutoff 1000.000
Resonanc 0.100000
Decay 0.379999
Filter e 0.000000
Oversamp 2.000000
Square a 1.000000
Saw amp 0.000000
Sub amp 0.600000
PWM str 0.000000
PWM freq 0.400000
AENV att 0.009999
AENV dec 0.100000
AENV sus 0.899999
AENV rel 2.000000

DEMO: Example Plugins in Action

- Standalone
- Unity Native Audio Plugin
- FMOD Studio
- VST 2.4

Summary

- Same code can easily be adapted for different plugin platforms
- FMOD Studio, Unity Native Audio Plugins, and VST 2.4 have similar interfaces

Example Unity Plugins

Unity C# Plugin Structure

```
class MySynthBehaviour : MonoBehaviour
{
    [...]
    void OnAudioFilterRead(float[] data, int channels)
    {
        int length = data.Length / channels;
        int idx = 0;
        for (int s = 0; s < length; ++s)
        {
            data[idx++] = COMPUTE LEFT SAMPLE
            data[idx++] = COMPUTE RIGHT SAMPLE
        }
    }
}
```

Sine Synth

```
float phase = 0.0f;
float freq = 200.0f;
const float secondsPerSample = 1.0f / 48000.0f;
void OnAudioFilterRead(float[] data, int channels)
{
    int length = data.Length / channels;
    int idx = 0;
    for (int s = 0; s < length; ++s)
    {
        float out = Mathf.Sin(phase * Mathf.PI * 2.0f);
        data[idx++] = out; // left channel
        data[idx++] = out; // right channel
        phase += freq * secondsPerSample;
        if(phase > 1.0f) phase = 0.0f;
    }
}
```

Distortion Effect (from 140)

```
int D = 0; // downsample factor
void OnAudioFilterRead(float[] data, int channels)
{
    if(D > 1)
    {
        for (int s = 0; s < data.Length; s+=2)
        {
            data[s]   = data[s / D * D]; // left channel
            data[s+1] = data[s / D * D + 1]; // right channel
        }
    }
}
```

Music Code Example

```
class SpookyBeat : MonoBehaviour
{
    float s = 0;

    void OnAudioFilterRead(float[] data, int channels)
    {
        int smp = 0, length = data.Length;

        while (smp < length)
        {
            s = ++s % 288000;
            float p = (s / 288000) * 0.5f;
            float pBar = (p * 8) % 1;
            float hhAmp = (0.13f + ((pBar * 4) % 1) * -0.09f);

            // mixer
            float output = BD(pBar * 8 / 3) * 0.8f
                + HH((pBar * 8) % 1) * hhAmp
                + bass(p) * 0.2f + bass(p - 0.024f) * 0.1f;

            for (int c = 0; c < channels; ++c)
                data[smp++] = output;
        }
    }
```

```
    // Bassdrum: sine with pitch and amplitude envelope
    float BD(float p)
    {
        float env = Mathf.Clamp01(0.1f - (p % 1f)) * 10f;
        float fr = 30f + env * 100f;
        float ph = (p % 1f) * fr;
        return Mathf.Sin((ph % 1f) * 6.28f) * env;
    }

    // Hihat: noise with amplitude envelope
    float HH(float p)
    {
        return Mathf.PerlinNoise(p * 2000, 0f) * (1f - p);
    }

    // Spooky bass: FM synth
    float bass(float p)
    {
        return Mathf.Sin(p * 4000 + Mathf.Sin( p * 4000
             + Mathf.Sin(p * 3.28f) * 1111))
             * Mathf.Sin(((p * 64 / 3f) % 1) * 3.141f);
    }
}
```

Summary

- Unity audio plugins can be written in C#
- Unity audio plugins have the same structure as other audio plugins
- Example synth and distortion effect
- Example music code

References

Karen Collins: "An Introduction to Procedural Music in Video Games" (2009)
https://bit.ly/2FfuN6E

Igor Dall'Avanzi: "Procedural Music in AAA: Rise of the Tomb Raider and the Dynamic Percussion System" (2016)
https://bit.ly/2HMEvjJ

Leonard J. Paul lectures about Pure Data for games
https://bit.ly/2FnIGjo

Questions?

Atari 2600 TIA Chip

- Integrated graphics and sound
- 2 DCOs pulse waveform
- 32 pitch values (not enough)
- 4 bit volume

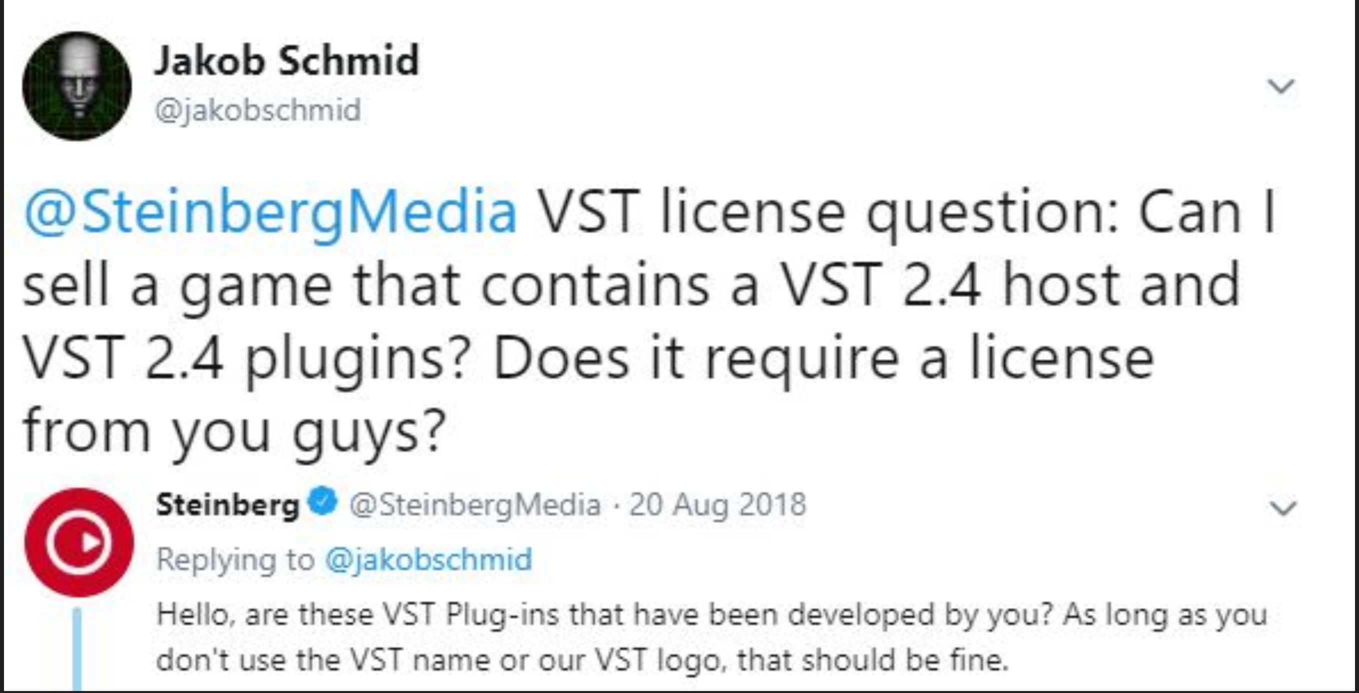
Audio Plugin Interface

- Audio system calls our code with buffer
- Our code writes samples to buffer
- Audio hardware outputs buffer to speaker

Wwise Sound Engine Effect Plugin

```
void IAkOutOfPlaceEffectPlugin::Execute(
     AkAudioBuffer * io_pInBuffer,   // input buffer
     AkUInt32        in_uInOffset,   // offset
     AkAudioBuffer * io_pOutBuffer ) // output buffer
{
    float *buf = io_pOutBuffer->GetChannel(0);
    RENDER [FIXME - how many samples?] TO buf
}
```

VST Plugins or Audio Units in Games?



Jakob Schmid
@jakobschmid

@SteinbergMedia VST license question: Can I sell a game that contains a VST 2.4 host and VST 2.4 plugins? Does it require a license from you guys?

Steinberg @SteinbergMedia · 20 Aug 2018
Replying to @jakobschmid

Hello, are these VST Plug-ins that have been developed by you? As long as you don't use the VST name or our VST logo, that should be fine.

VST Plugins or Audio Units in Games?

If plugin is open source or homemade:

- Relatively easy to adapt to game audio plugin

VST Plugins or Audio Units in Games?

Most interesting VST/AU plugins are *not* open source.

Technically they could still work in a game, however:

- Illegal distribution: Most VST/AU plugins licensing models do not allow for redistributing to potentially millions of users in a game.
- Limited platforms: Most VST/AU plugins are available in binary form for Windows and Mac OS X, but not for Android, iOS, PS4, Xbox One, etc. so would only work on computers.

VST Plugins or Audio Units in Games?

- Possible.
- Not practical!