Adaptive and Generative Music in Games

Sonic College 2025

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Overview

- Early Game Audio Hardware
- Adaptive and Generative Music in Games
- Combining Approaches
- Plugin Platforms
- Example Unity Plugins

Early Game Audio Hardware

Hardware synthesizers

- 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

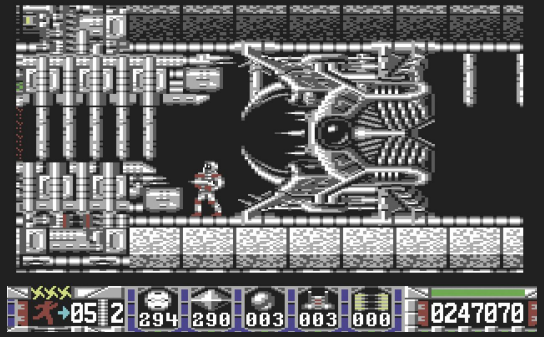
From Synthesizers to Samplers

- 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
- This mirrored the general evolution in music technology

Amiga 1000 (1985),
sample-based audio hardware

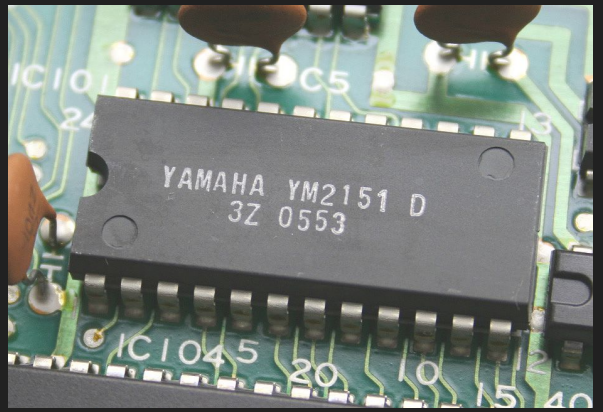
Commodore 64 SID Chip

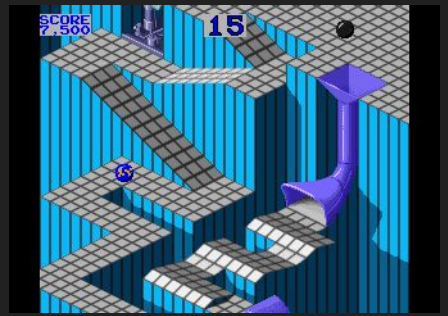
- 3 DCOs
- Waveforms: pulse, triangle, saw, noise
- Ring modulation, oscillator sync
- Multimode filter: low-, high-, bandpass (6dB/12dB rolloff)
- 3 Envelope generators



Yamaha YM2151

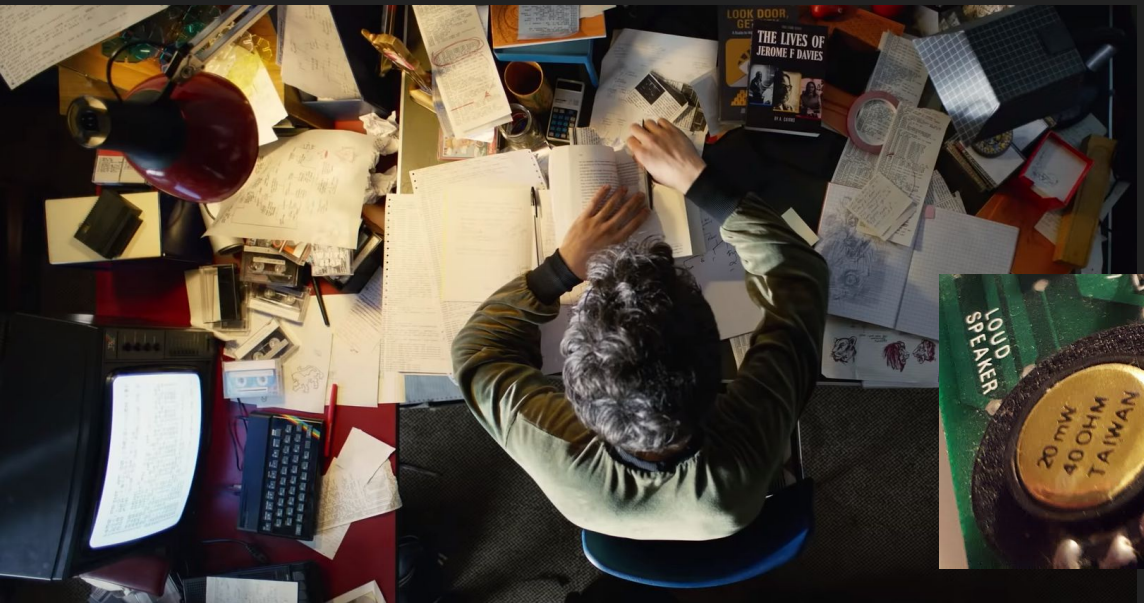
- FM synthesis, 4 operators
- 8 channel polyphony
- Used in many arcade games by Atari, SEGA, and Konami
- See also https://vgmrips.net/packs/chip/ym2151

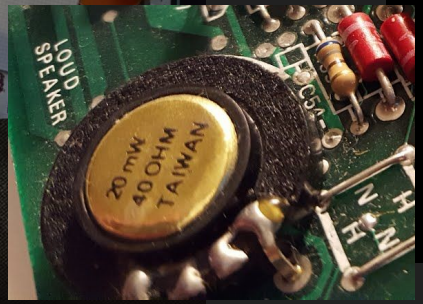




ZX Spectrum Speaker

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





Summary

- Hardware based realtime synthesis was the norm until mid 1980s
- From around 1985, sample-based hardware started to become the norm
- Early audio hardware ranged from 1-bit tone generators to subtractive synthesis and FM synthesis.

Adaptive and Generative Music in Games

How would you define these terms?

- Adaptive game music
- Generative game music.

Adaptive Music

Music that changes as a result of a change in game state

Key and Tempo changes

Ex.: Space Invaders

Vertical Remixing

Dynamically changing instrumentation based on game state

Ex.: Super Mario World (Yoshi bongos)

Horizontal Re-sequencing

Hard re-sequencing

Ex.: Xenon (pinball)

Re-sequencing with transitions

Ex.: Monkey Island 2

Synchronized Scoring

Syncing Music to Picture also known as 'Mickey Mousing'

Ex.: Dig Dug

Generative Music

Music that is generated at runtime. Can be adaptive or non-adaptive

Interactive Music

Music generated directly from player input

Ex.: Tetris Effect

Note-generative music

Individual notes are generated, e.g. MIDI messages

Ex.: Spore

Realtime synthesis

Sound signal is generated at run-time

Ex.: Chronos (1-bit music)

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Space Invaders

- Arcade 1978
- Plays descending notes

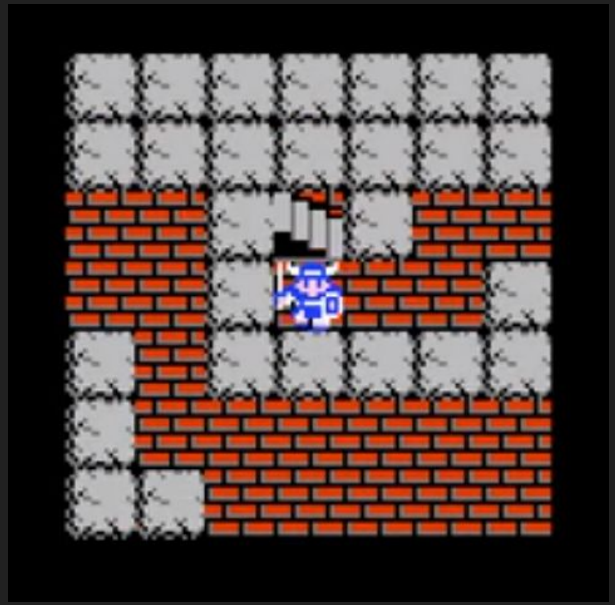
  `C#1, B0, A0, G#0`

- Accelerates from 69 BPM to 690 BPM as enemies are killed and move faster
- Adaptive using tempo change

space invaders

Dragon Warrior

- NES 1986
- Dungeon music changes key with dungeon level
- Helps player finding their way around?
- Adaptive using key change



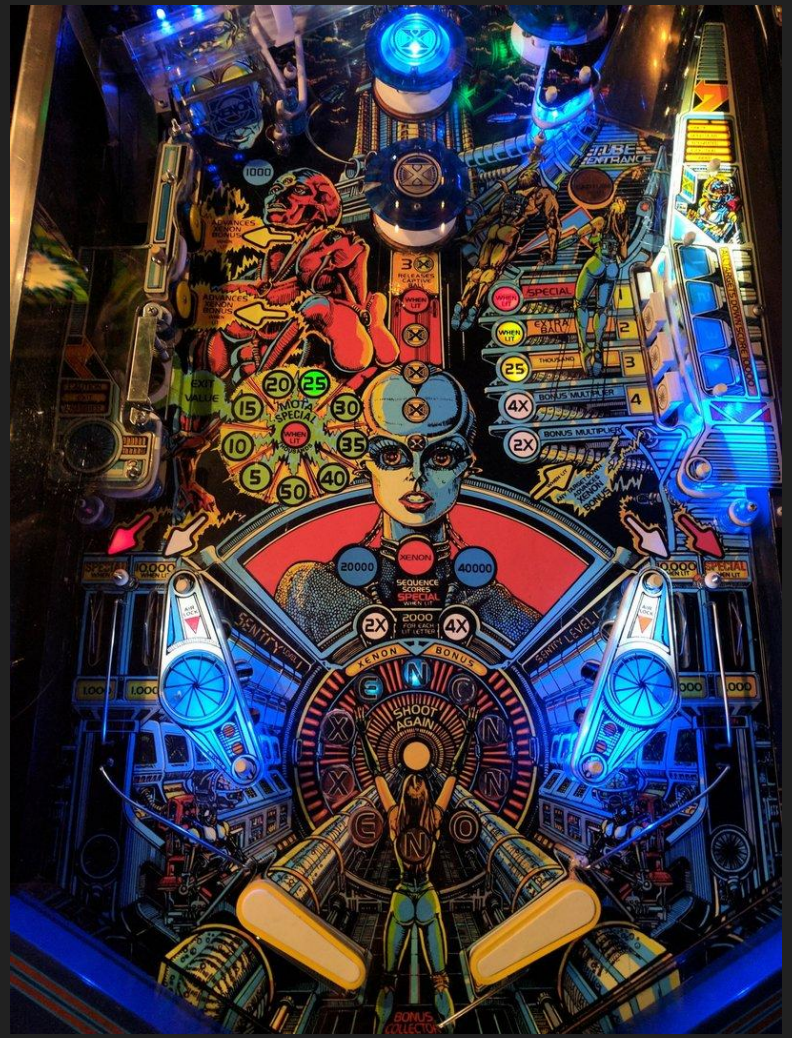
Super Mario World

- SNES 1990
- When you ride Yoshi, a bongo track is added to the music
- Vertical remixing

super mario world

Xenon

- Pinball 1980
- Switches between music loops and voice samples
- Designed and composed by Suzanne Ciani
- Hard horizontal re-sequencing



iMUSE

- DOS 1991
- Interactive Music Streaming Engine
- LucasArts
- First used in 'Monkey Island 2: LeChuck's Revenge', DOS 1991
- Adaptive MIDI music with seamless transitions and feedback to gameplay
- Horizontal re-sequencing with transitions

monkey island 2

Dig Dug

- Arcade 1982
- Each step of your little guy is accompanied by a musical note
- ~ Mickey Mousing
- Synchronized scoring

dig dug

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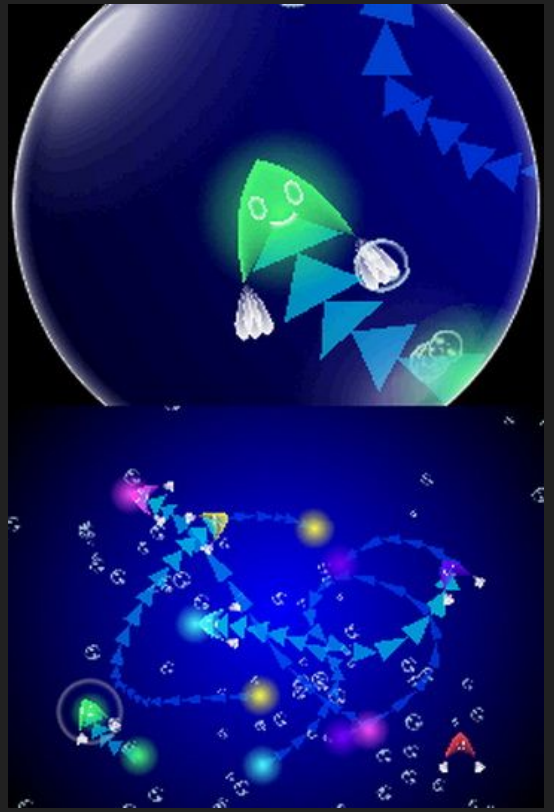
Otocky

- NES 1987
- Music generated by gameplay elements
- Hardware NES synth, 5 channels + sample playback
- Interactive music

otocky

Electroplankton

- NDS 2005
- Generative music toy
- Uses collisions from 2D physics model to generate notes
- Note-generative



electroplankton

Rise of the Tomb Raider

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

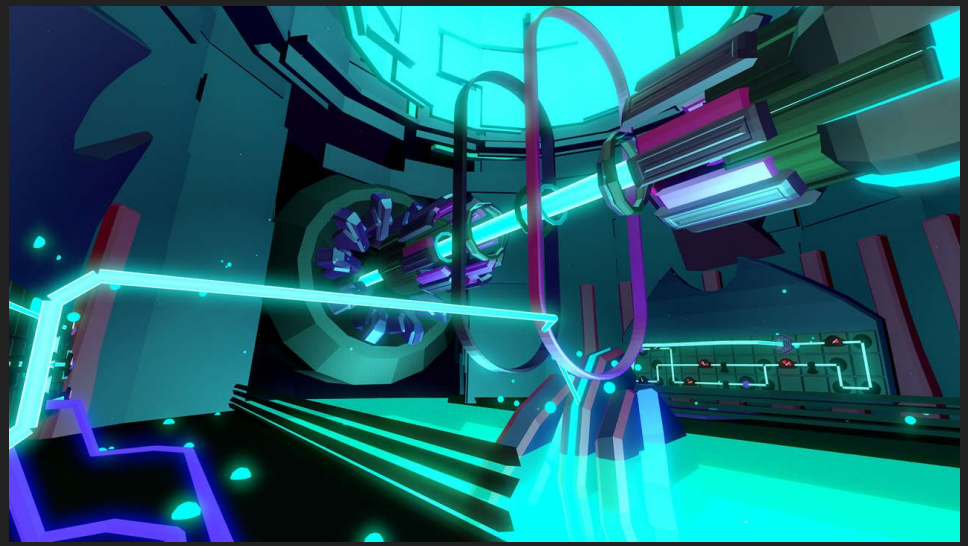
tomb raider

Spore

- Windows 2008
- Editors (such as creature editor) generates notes in realtime based on choices (e.g. meat-eater or vegetarian)
- Most sounds are samples, some realtime synthesized
- Kent Jolly and Brian Eno
- Uses PureData
- Note-generative

FRACT OSC

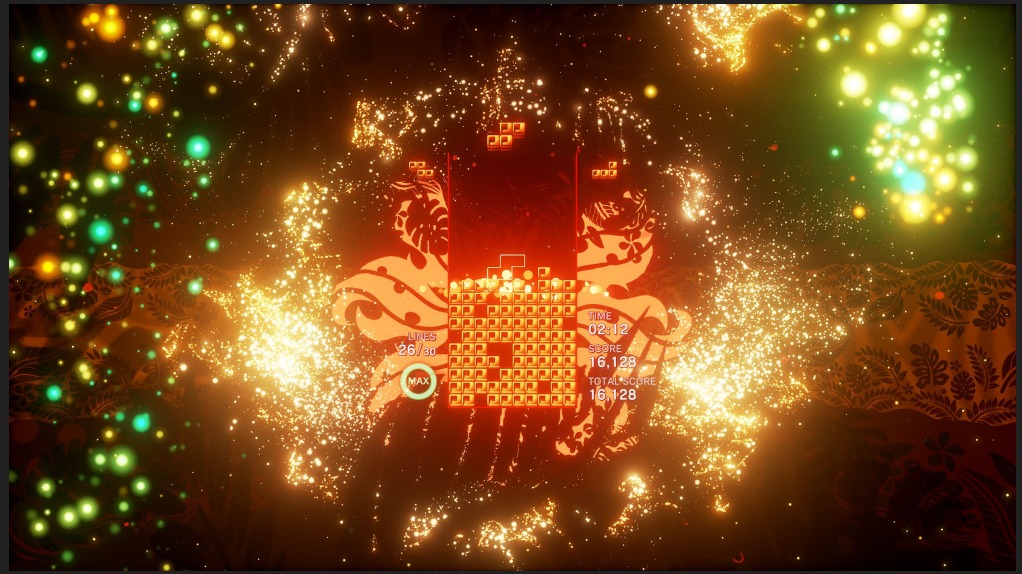
- Windows 2014
- First-person puzzle game where you construct a realtime-synthesized piece of music
- Uses PureData
- Realtime synthesis



Combining Approaches

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
- Each level is an music toy that the player can play with



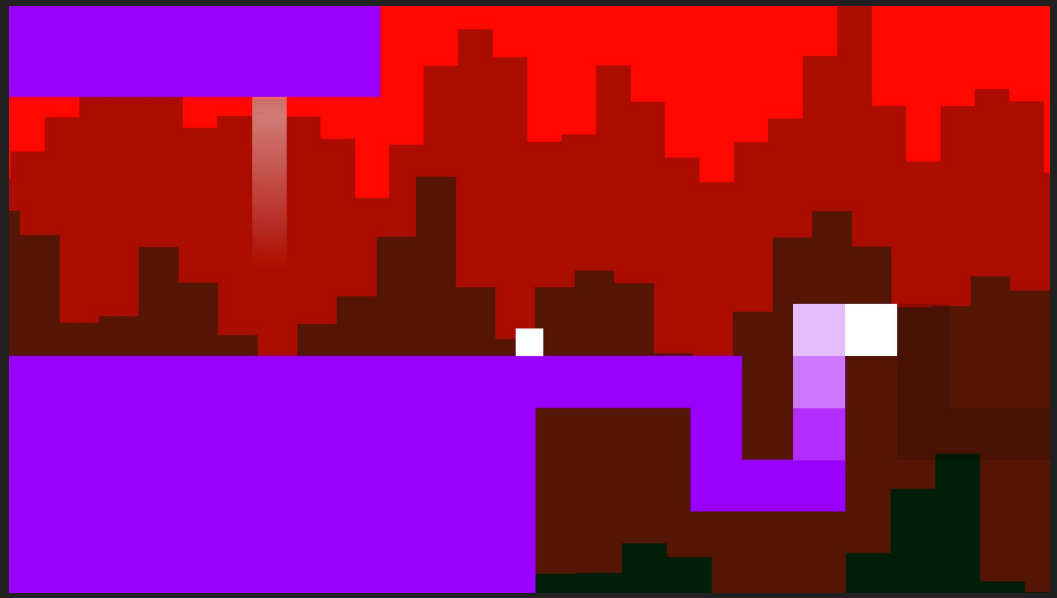
tetris effect

Tetris Effect: Music System

- Hybrid interactive/adaptive music
- Interactive: player input is quantized and plays notes
- Vertical remixing (possibly): according to level progress
- Horizontal re-sequencing with transitions: big transitions according to level progress

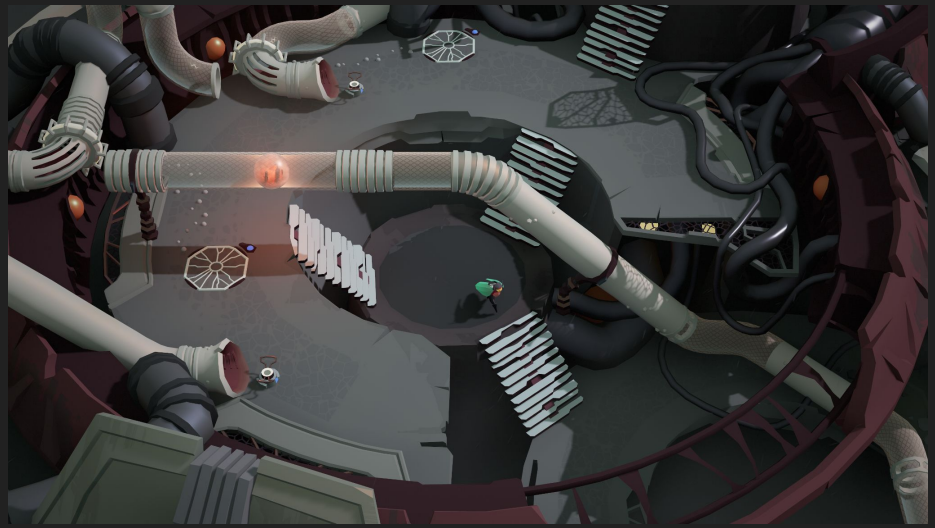
140

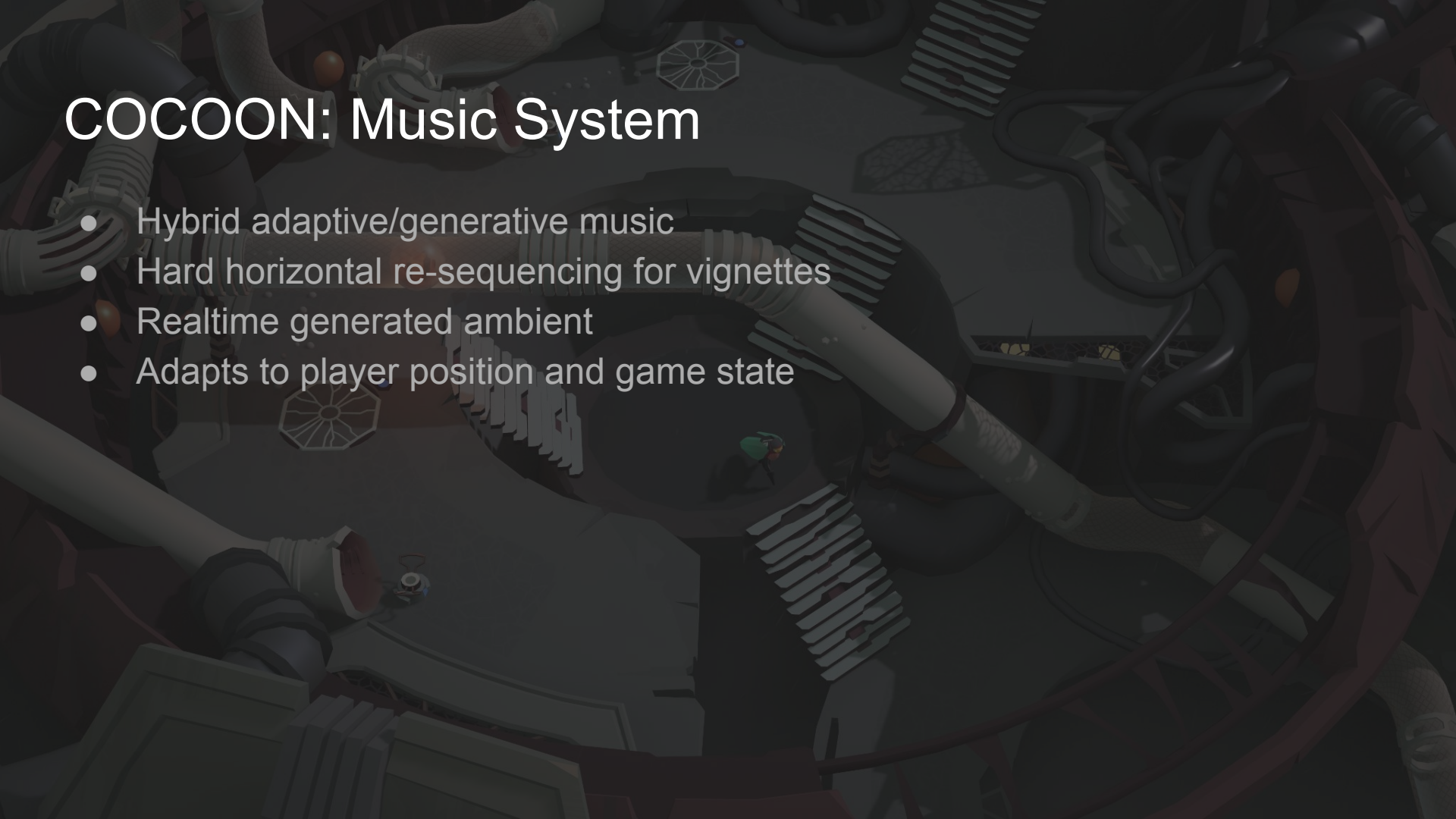
- Windows 2013
- Vertical remixing used to dynamically change music with player movement
- Hard horizontal re-sequencing used when delivering a new key



COCOON

- Windows/consoles 2023
- Vignettes: hard horizontal re-sequencing using FMOD Studio
- Ambient: realtime generated using custom FMOD synthesizer plugins
- Boss fights: combines all techniques
- Ambient adapts to player position
- Boss fights adapts to game state





COCOON: Music System

- Hybrid adaptive/generative music
- Hard horizontal re-sequencing for vignettes
- Realtime generated ambient
- Adapts to player position and game state

Rytmos

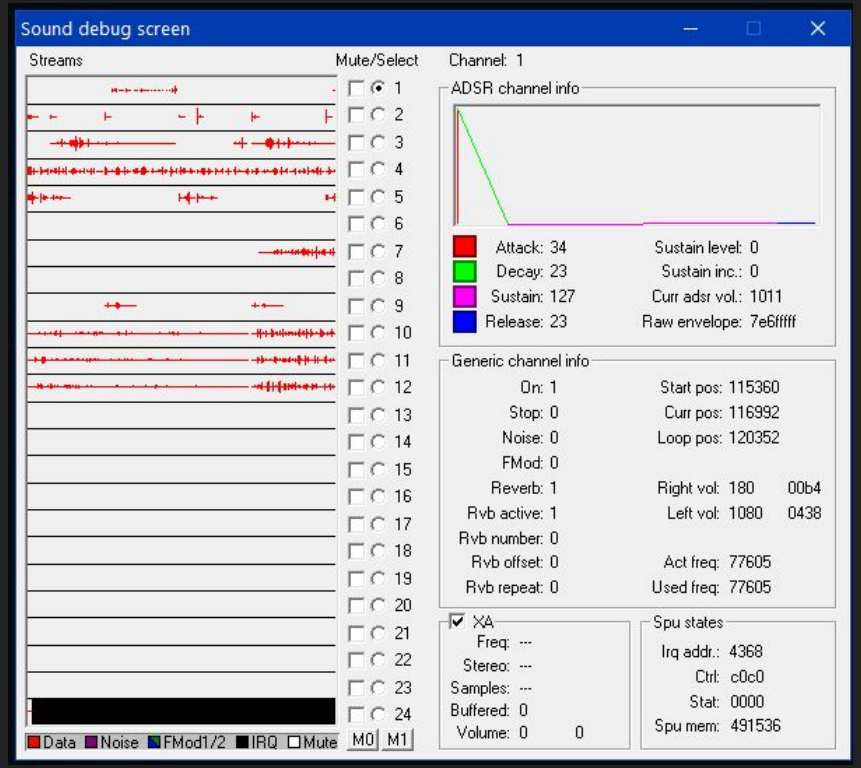
- Switch, Windows 2023
- Music by Niels Böttcher
- Note-adaptive sequencing based on puzzle state
- Uses scales carefully selected to fit music genre
- A few realtime Unity Native Audio Plugin effects by me

Mid-late 1990s

- Sample-based audio hardware
- Cheaper memory makes sampled sound more useful

PlayStation Audio Hardware

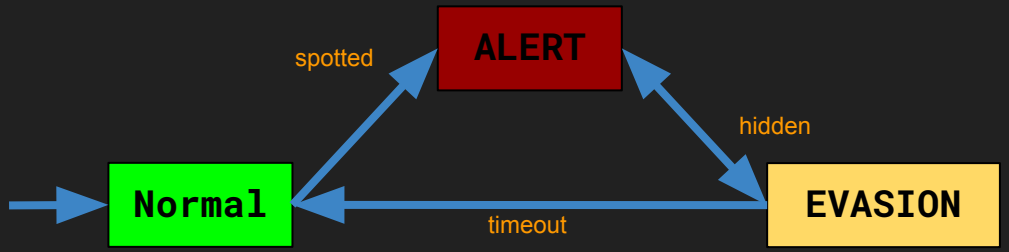
- 24 channels, 16-bit, 44.1 KHz
- Each channel:
  - looping
  - pitch
  - amplitude envelope
  - panning
  - effect send on/off
- 1 stereo streaming CD track
- 1 configurable delay / reverb effect
- 512 KB audio memory



Metal Gear Solid

- PlayStation 1998
- Stealth action game
- Directed by Hideo Kojima

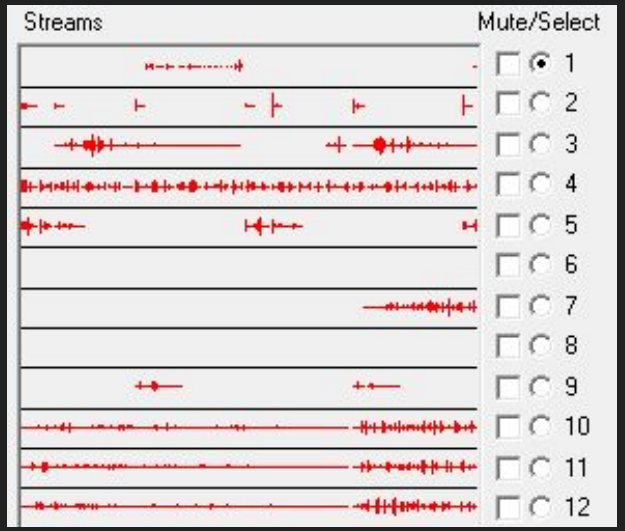
Metal Gear Solid: Game States



- Normal >> ALERT: immediately when spotted
- ALERT >> EVASION: automatic when hidden for a while
- EVASION >> Normal: automatic when hidden for a while

Metal Gear Solid: Music System

- 12-track sample-based sequencer
- Follows game states:

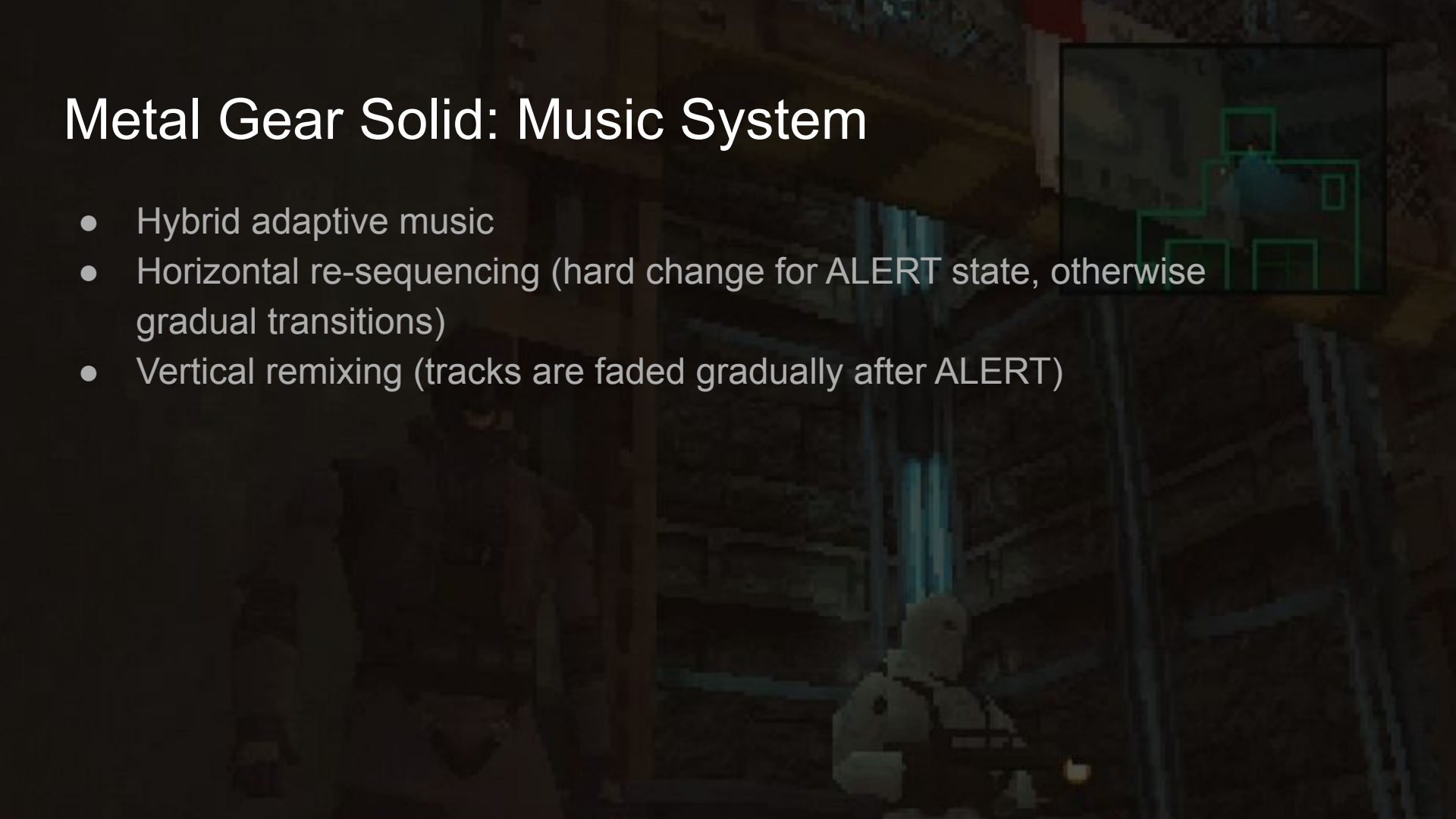


- Normal >> ALERT: immediately play **!** sound (diminished chord), key and tempo change, exciting music
- EVASION: some tracks fade out and tempo slows down
- EVASION >> Normal: Switch to calm background music

metal gear solid

Metal Gear Solid: Music System

- Hybrid adaptive music
- Horizontal re-sequencing (hard change for ALERT state, otherwise gradual transitions)
- Vertical remixing (tracks are faded gradually after ALERT)



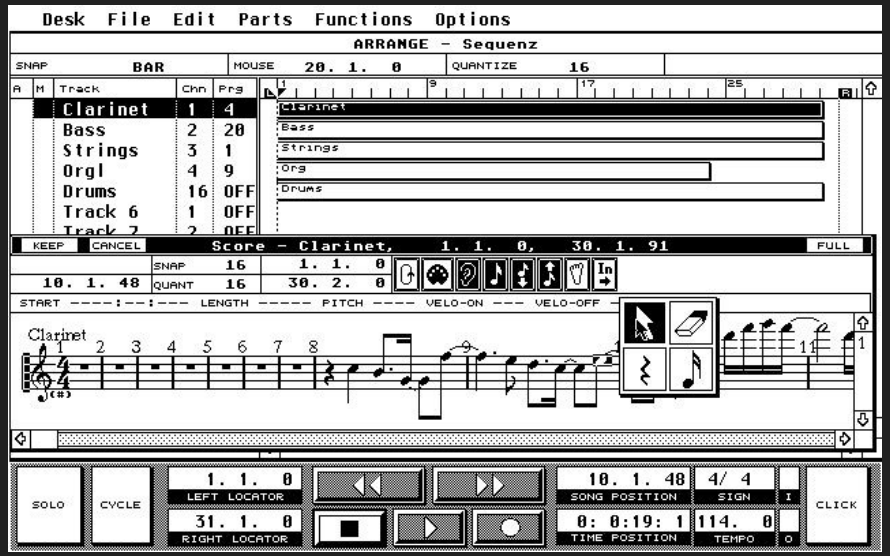
Summary

- Combining approaches is powerful
- Tetris Effect, Metal Gear Solid, 140, COCOON, Rytmos

Audio Plugins

MIDI-like Sequencing

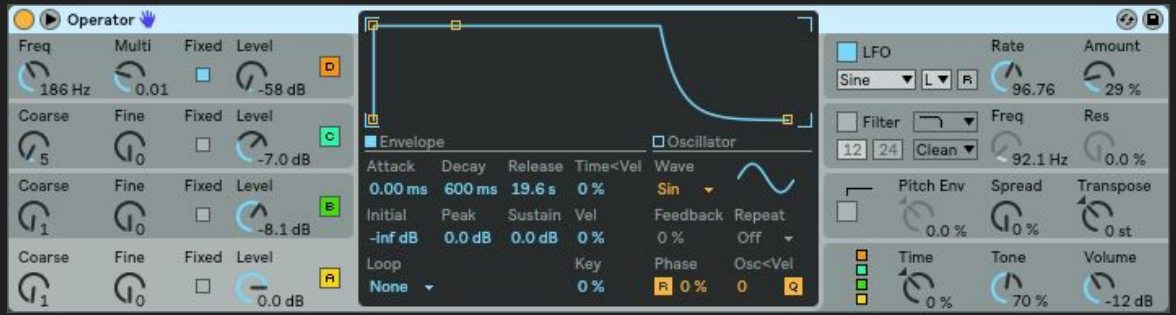
- Sequencing of samples or real-time synthesis
- Key changes
- Removing notes
- Procedural / generative music



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



Ableton Live 10: Operator

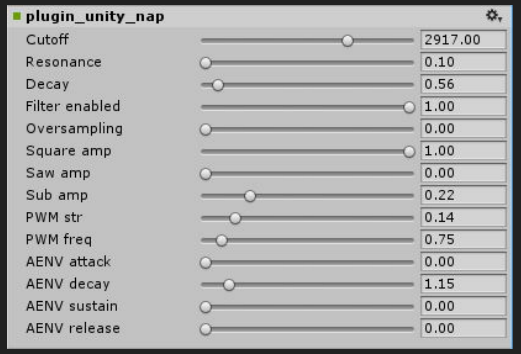
Modern Realtime Synthesis

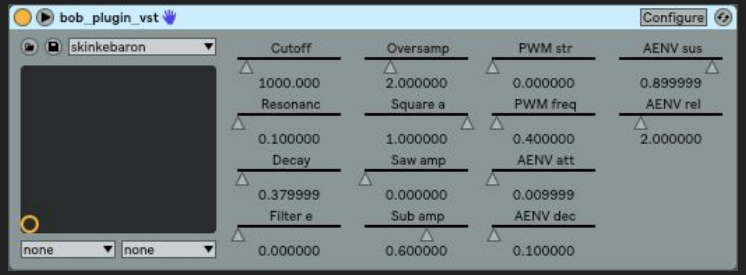
- Implemented as audio plugins in sound engines
- Normally rendered on CPU, not in dedicated hardware

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)





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];
}
```

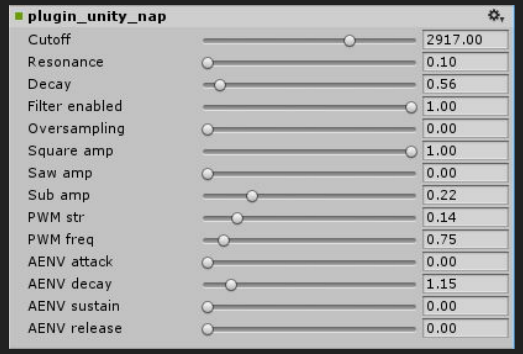
Summary

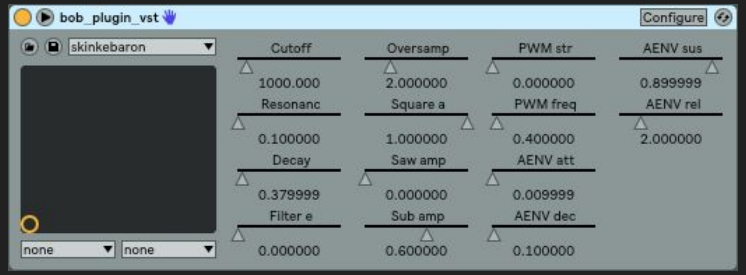
- Realtime synthesis is done using software audio plugins
- Different audio software have different plugin types
- Audio plugins output samples to audio buffer
- Synths and effects are very similar, except for their input

Plugin Platforms

Plugin Platforms

Same code,
different
platforms



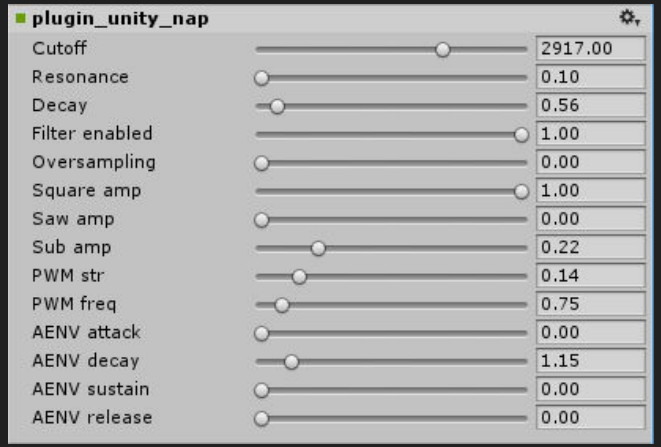


FMOD Studio Plugin

```
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;
    }
```

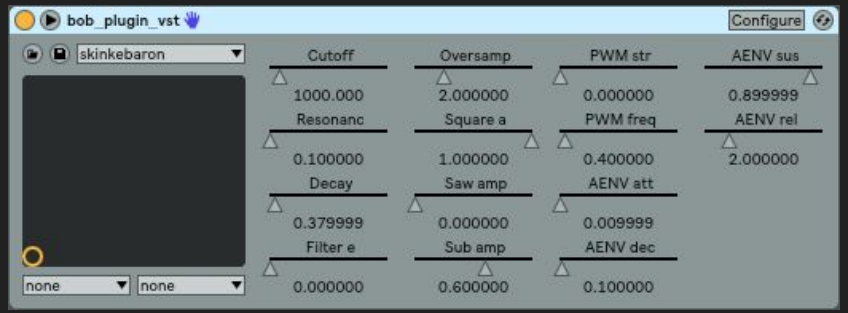
Unity Native Audio Plugin

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



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
}
```



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: School of Video Game Audio lectures about Pure Data for games
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References

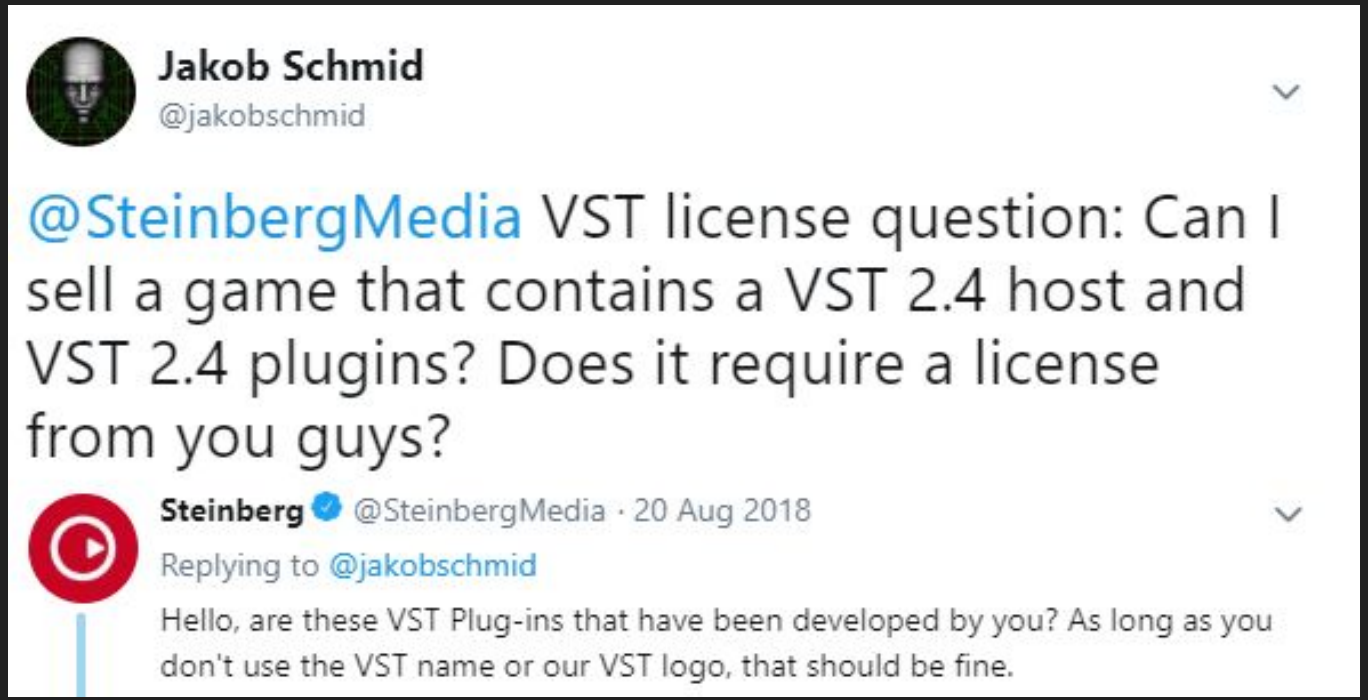
Nameless Algorithm: "Digital Signal Processing References" (2024)
https://namelessalgorithm.com/computer_music/blog/dsprefs/

Questions?

Control

- PS4, Xbox One 2019
- Martin Stig Andersen
- Micro-sequencing

VST Plugins or Audio Units in Games?



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!

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
}
```

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

DEMO: Example Plugins in Action

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

Atari 2600 TIA Chip

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