

# **Way Beyond the Expected**

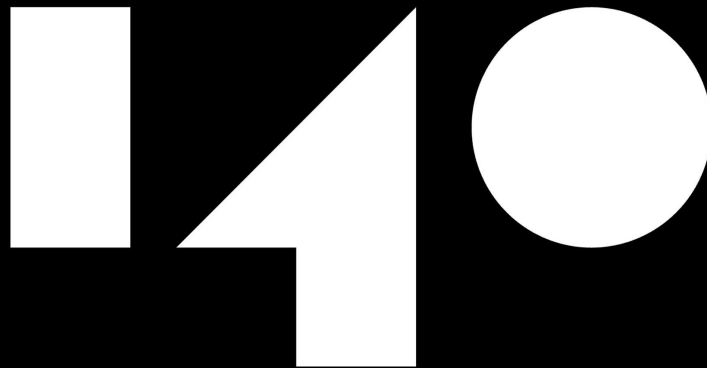
Jakob Schmid, Spilbar 2015

# Me

Jakob Schmid

Audio programmer at Playdead

Composer by night



**IGF award 2013**

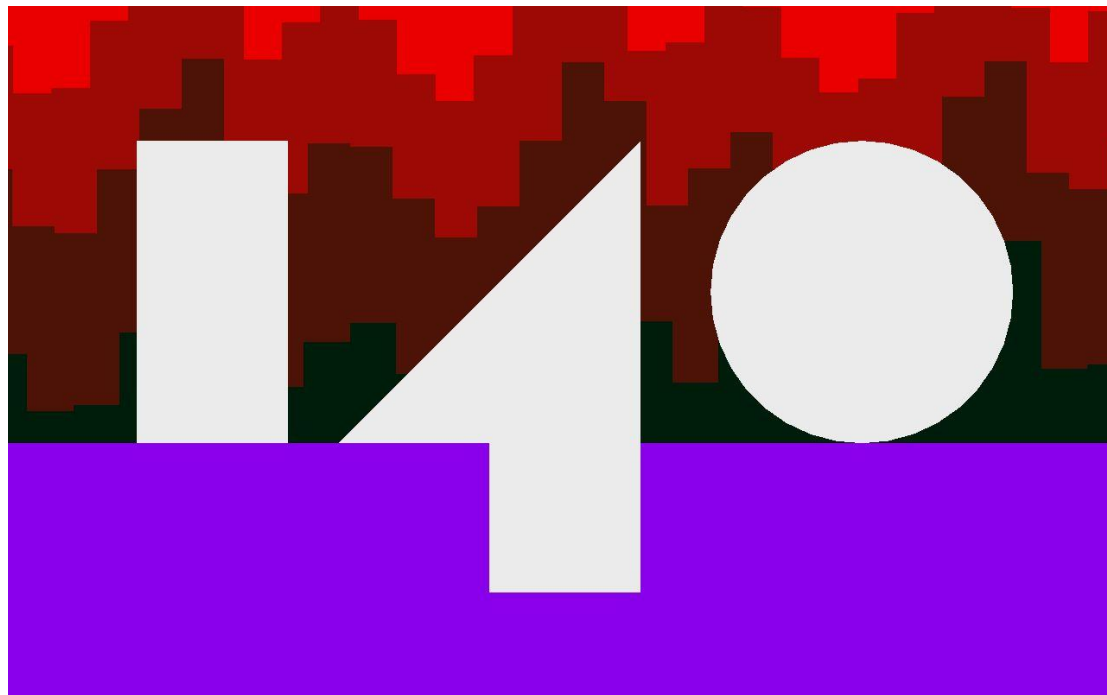
Excellence in Audio

**Spilprisen 2014**

Sound of the Year

**Nordic Game Award 2014**

Artistic Achievement



**By Jeppe Carlsen**

# Way Beyond the Expected

- Composers and programmers breaking hardware limits
- 3 examples of games from the 1980s
- Modern sample-playing sound cards did not exist yet
- 3 very different approaches to sound
- Not chronological



SYSTEM I™

# MARBLE MADNESS™

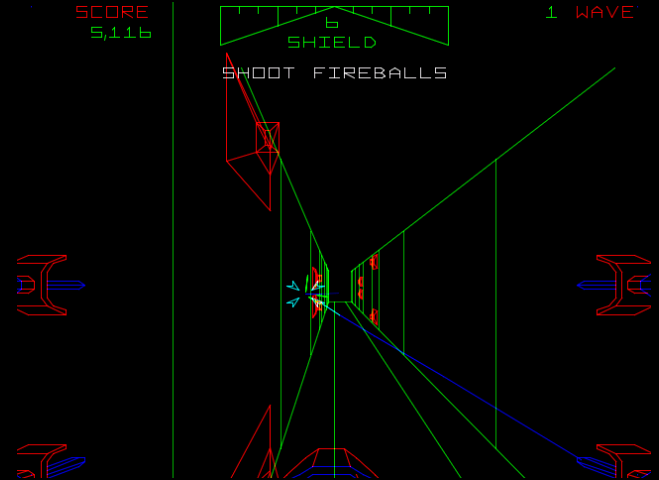


# Game Music of the Early 80s

BurgerTime (1982)

Mr. Do's Castle (1983)

Star Wars (1983)



# Marble Madness Gameplay

# The Sound of Marble Madness

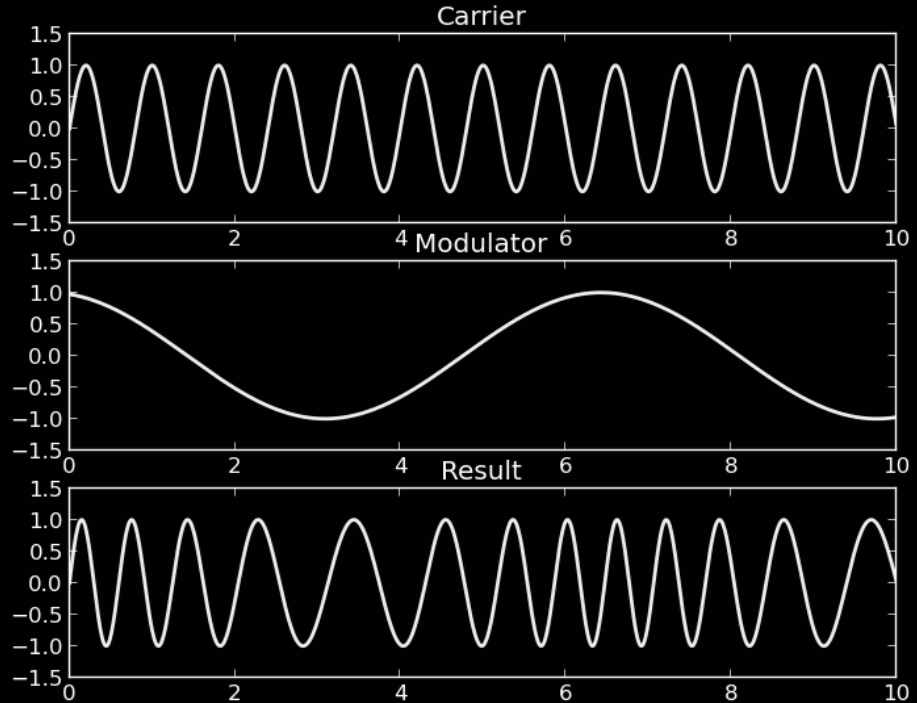
What defines the unique sound?

- Frequency Modulation Synthesis



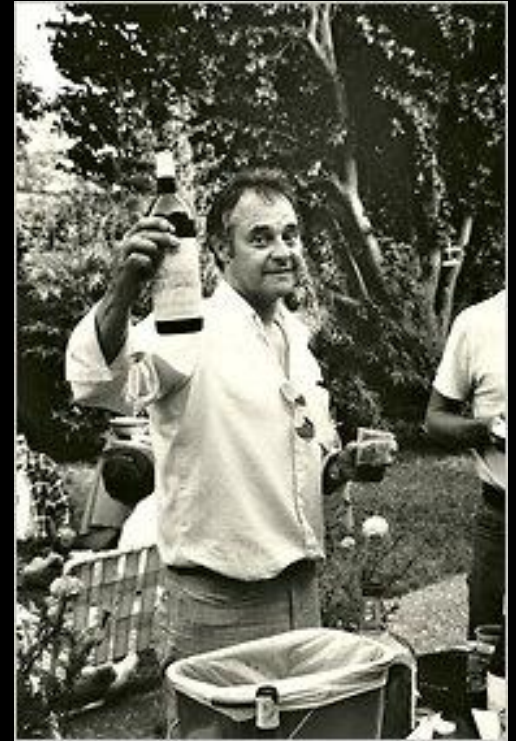
# Frequency Modulation (FM) Synthesis

$$\sin( c*t + \sin( m*t ) )$$



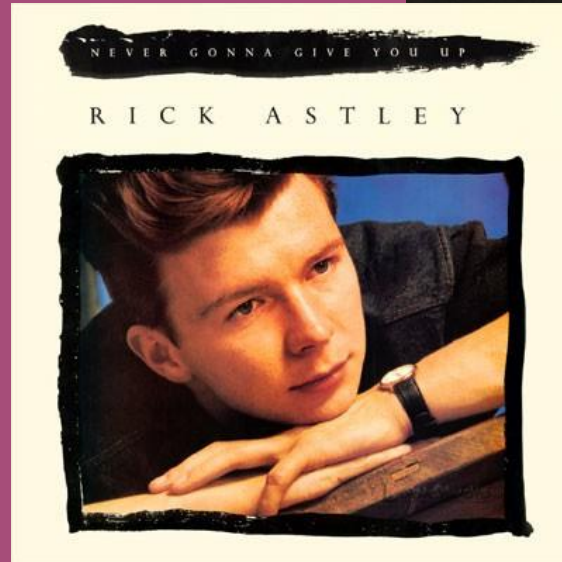
# FM Synthesis

- John Chowning, 1967
- Patented by Stanford University in 1975
- Licensed to Yamaha



# 1983: FM Synthesis

Yamaha DX7



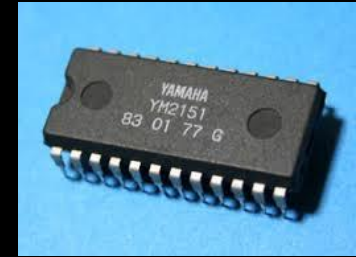
DX SYNTHESIZER  
1983 A.D.

DX

# 1984: FM In The Arcades

Atari arcade games

- Yamaha chip YM2151



# 1984: Marble Madness

- First Atari arcade game with FM sound



# Mark Cerny

- Game design by Mark Cerny
- Joined Atari when he was 17



# Marble Madness Development

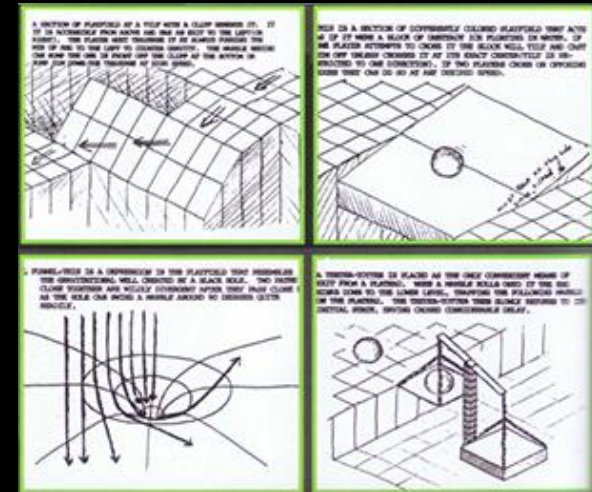
Ambitious project!

Raytracer generated tilemap

- 16 x antialiasing
- shadows



- 1-2 months to make a level
- 12 levels were made
- 6 were scrapped



# Marble Madness Music and SFX

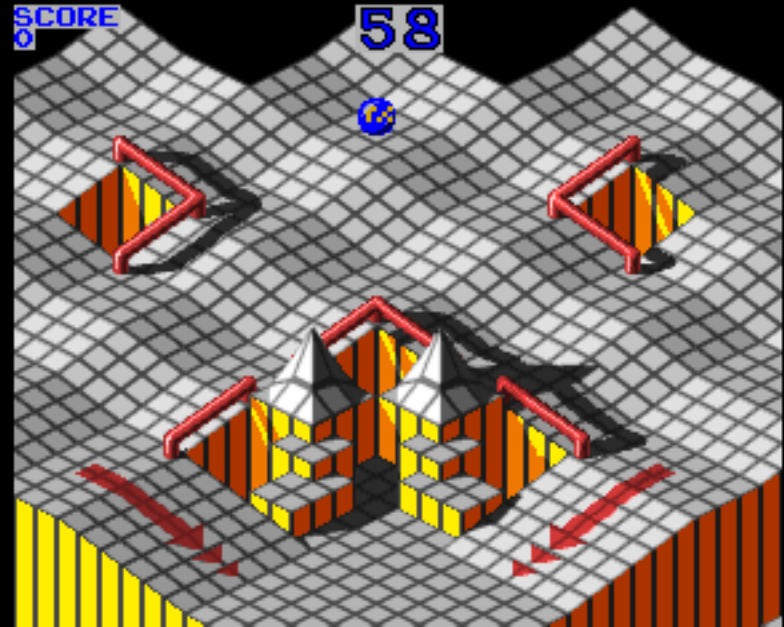
- Brad Fuller and Hal Canon





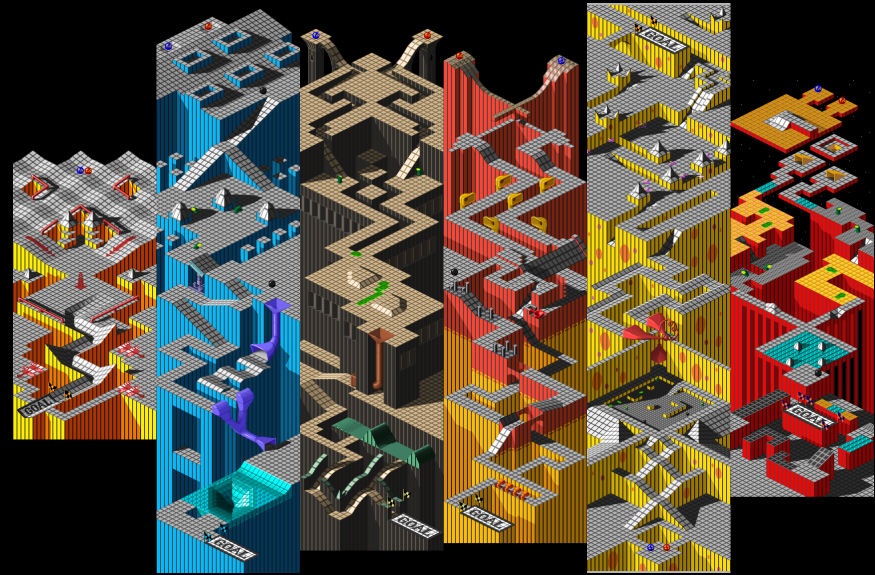
# PRACTICE Race

- Ticking clock
- “Hand-played” chords
  - simulating a human musician

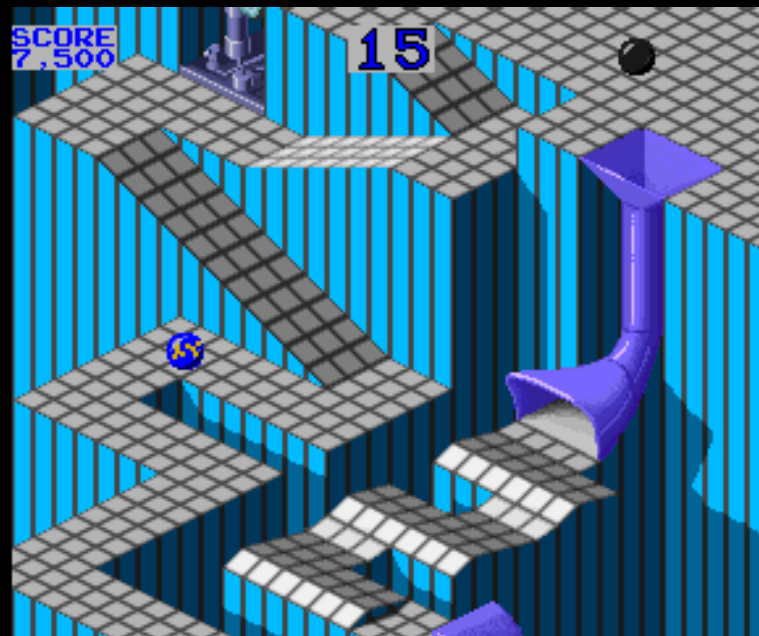


# Anticipatory Sound Effects

- Goal sound effect anticipates BEGINNER Race music

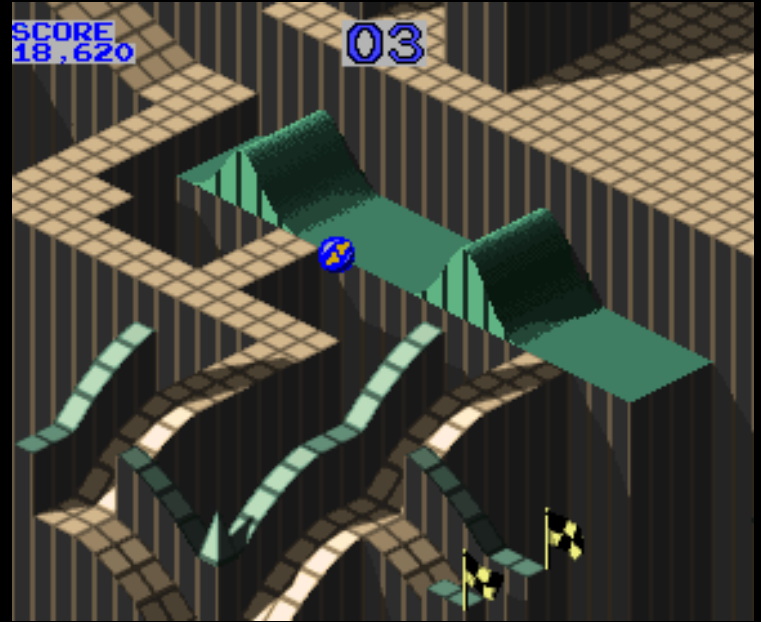


# BEGINNER Race



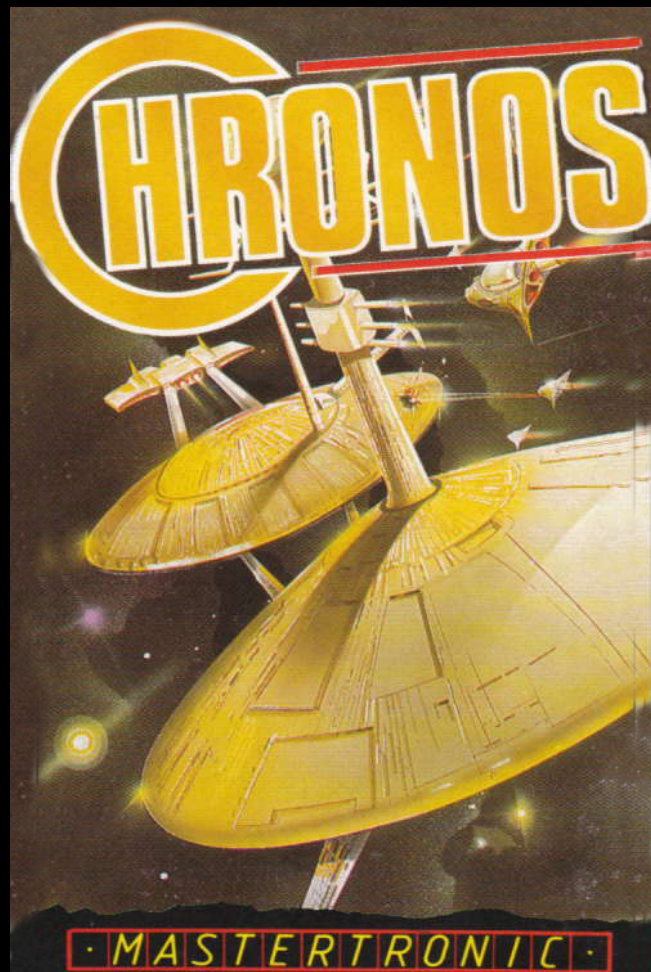
# INTERMEDIATE Race

- Clock chime
- Tempo varies
- Syncopation
- Orchestral instrumentation
- Stereo panning



Annoying sound anticipates annoying traps in the AIR RACE

Next Game



# Chronos Gameplay

# 1982

- Most popular in Europe
- Rival: Commodore 64
- No custom chips

## Sinclair ZX Spectrum

*16K or 48K RAM...  
full-size moving-  
key keyboard...  
colour and sound...  
high-resolution  
graphics...*

*From only  
**£125!***



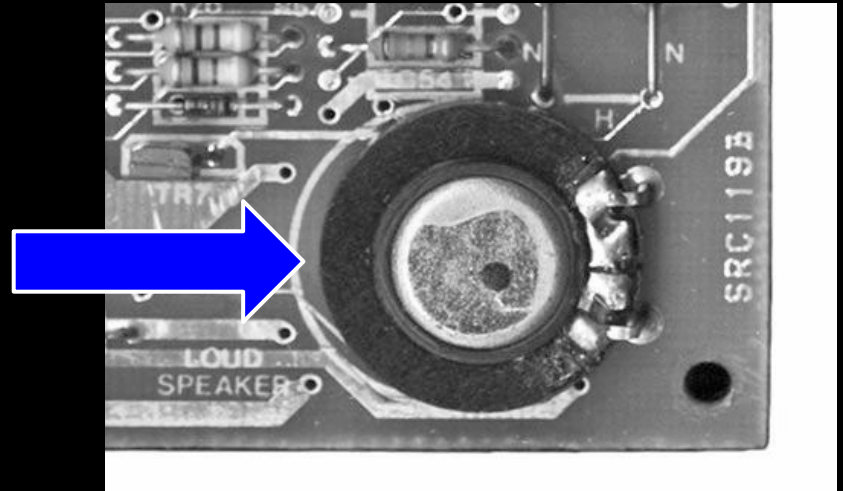


# ZX Spectrum Sound

Z80 processor, 3.5 Mhz (a bit faster than the C64)

Built-in speaker

- beep at given frequency
- fixed volume

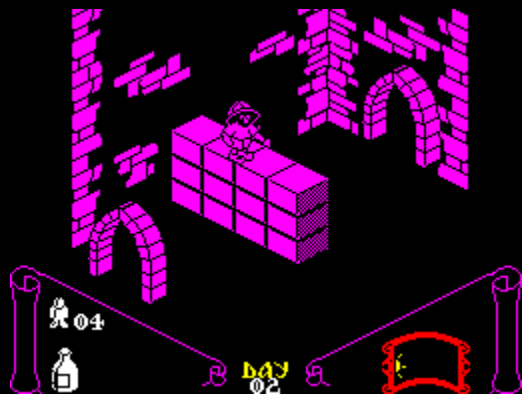
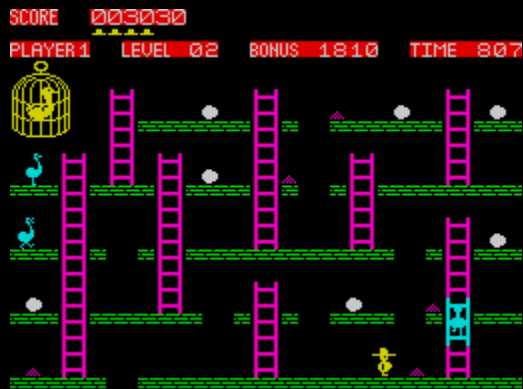


# ZX Spectrum Music

Chuckie Egg (1983)

Knight Lore (1984)

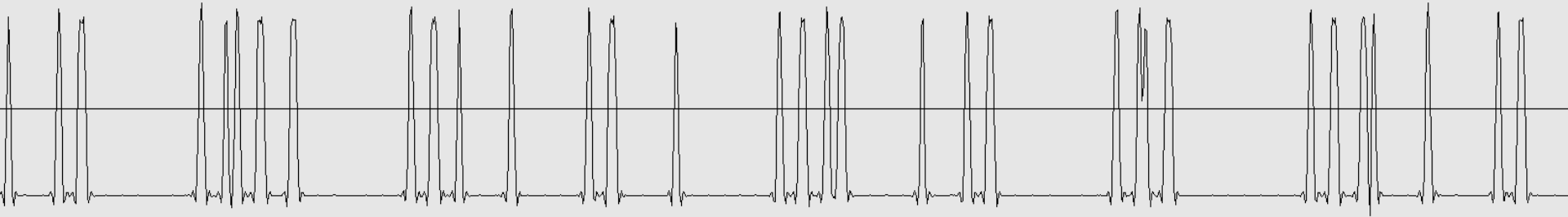
Renegade (1987)



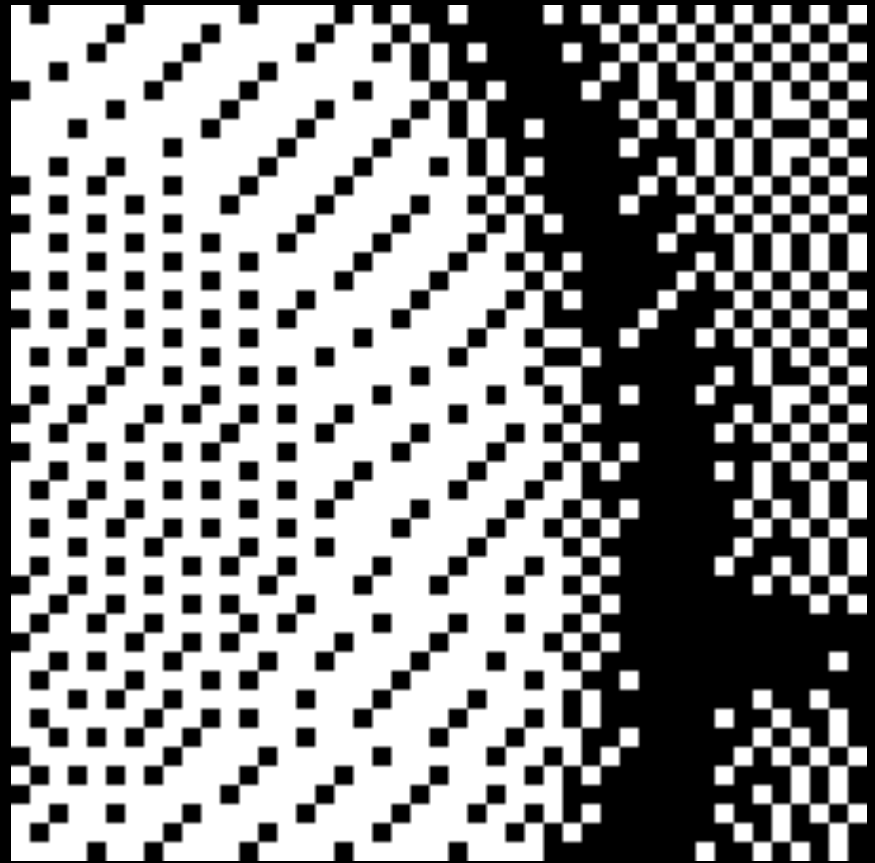
# 1-bit Music

Beeper is either on or off

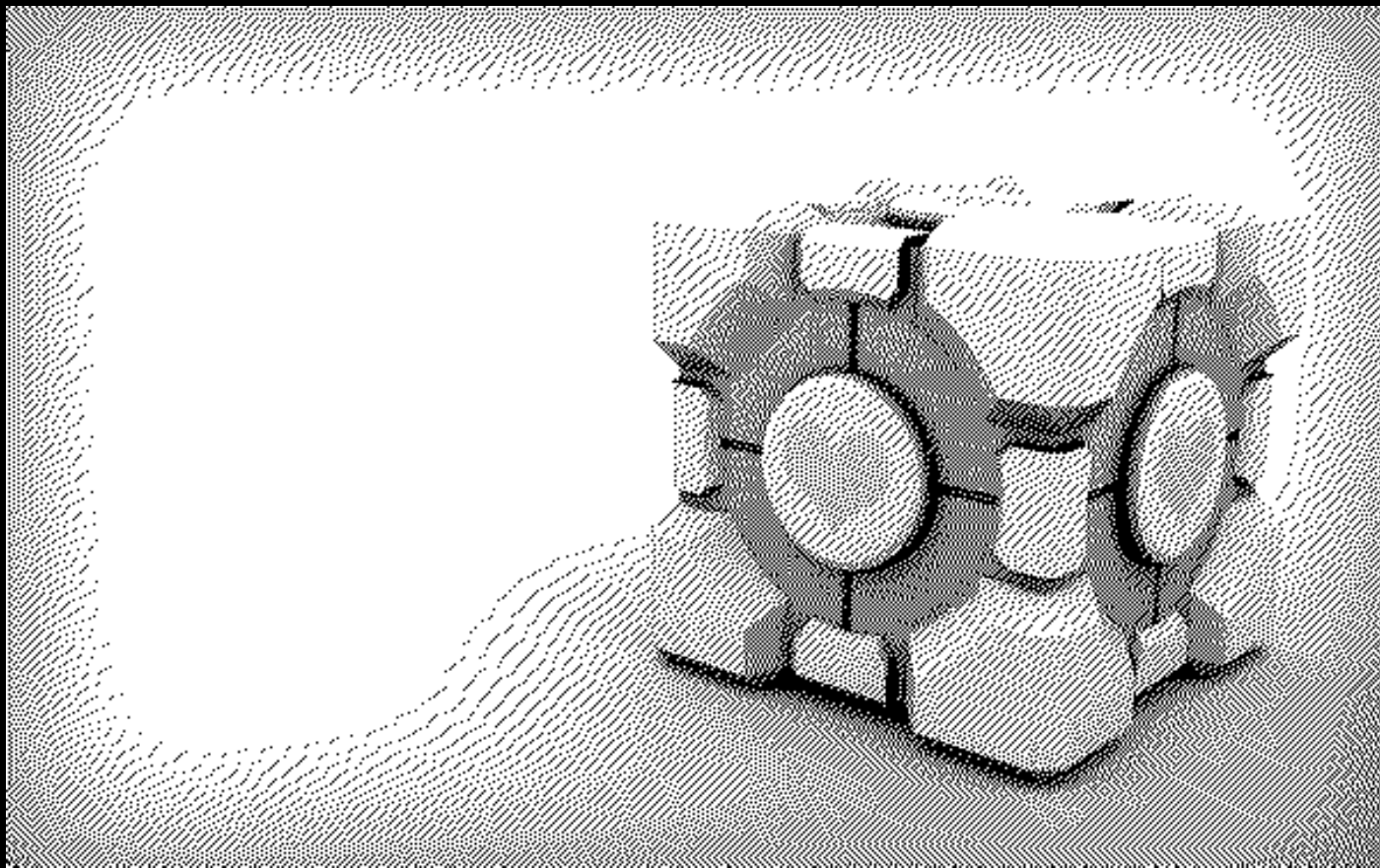
What can you do with only 1 bit?



# 1 Bit Graphics



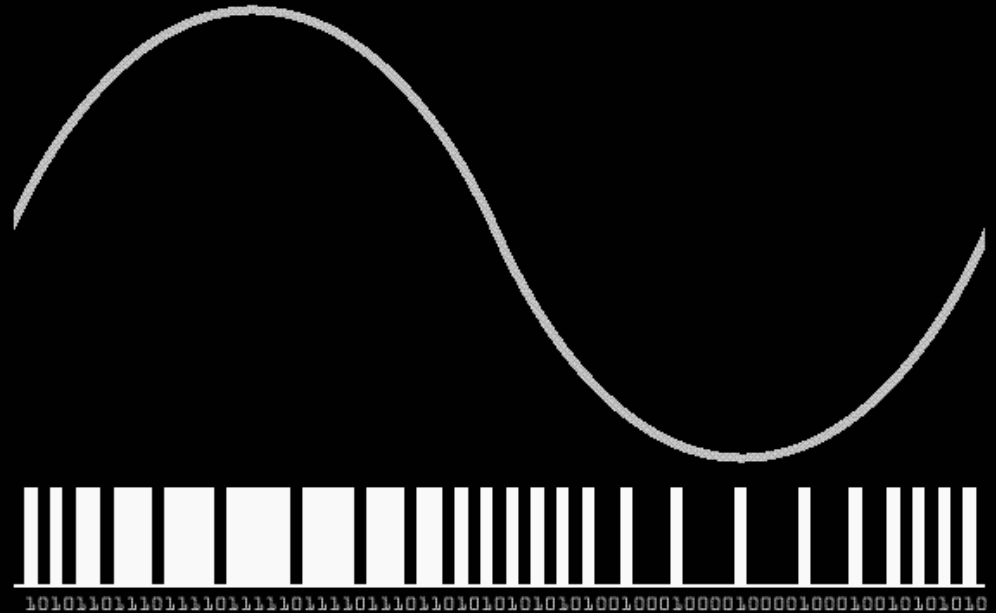
# 1 Bit Graphics



# What can you do with 1 bit?

Everything!

- If you have enough of them



# Tim Follin

## 15 years old



This amazing three-channel sound routine is the product of the versatile musical talent of Tim Follin, the man behind the tunes on Mastertronic's *Agent X*, and Firebird's spectacular *Sentinel*. If you thought these were the corkiest sonics you've heard on any Speccy game, you'll be thrilled to atoms over this chunk of machine code music!

Tim is currently working on a brilliant new routine for a 6 channel sound with chorus bass, 128K snare drum, echo on/off/delay time, portamento, and full ADSR! This fabby routine is to appear on a brand new game called *Red 5*, by Peter Gough, so keep a look out for it in the near future.

### Method

The code begins at 40000 and is a mere 1340 bytes long. First CLEAR 39999, then LOAD

# START 2

by Tim Follin

""CODE. To hear the tune, simply RANDOMISE USR 40000. Any key breaks.

Note: Tim has asked us to say that although he doesn't mind you using the tune in your own programs, he does retain copyright on it, so it can't be used for commercial games.

### Hex Dump

Type the following hex dump into the hex loader and save as SAVE "TUNE" LODE 40000,1340. Good luck!

```
40000 F3 21 E8 03 22 5A 90 00 1013
40008 01 A2 00 00 7E 00 3C 02 88F
40016 7C 9C 08 23 00 4A 01 00 1061
40024 0A 00 22 37 00 00 23 00 0A5
40032 23 08 7E 00 03 2C 00 00 902
40040 7C 01 32 5A 90 00 7E 02 0773
40048 32 0F 9B 08 23 00 23 00 1035
40056 23 48 9C 3A 90 32 0E1A
40064 5B 90 3A 5C 90 32 30 00 060
40072 23 48 57 90 00 4A 00 00 1100
40080 4E 01 00 5E 02 1E 0A 3E 522
40088 01 32 5F 90 32 5E 90 03 802
40096 8A 0C AF 08 FE 2F 6A 1F 1298
40104 02 88 0C 00 23 08 23 50 1267
40112 23 00 7E 00 47 C2 8B 9C 0774
40120 7A 07 03 3A 5F 90 AF 25 1069
40128 20 11 0F 83 1F 41 10 FE 1028
40136 3E 10 03 FE 91 47 10 FE 1029
40144 05 6A 00 20 20 11 AF 03 0631
40152 FE 41 10 FE 3E 10 03 FE 1132
40160 91 47 10 FE 30 6E 01 1D 0831
40168 20 11 AF 03 FE 41 10 FE 1028
40176 3E 10 03 FE 91 47 10 FE 1029
40184 0E 5A 02 10 C2 AF 0E 1E 1029
40192 0A 3A 5E 90 AF 7A 3F 0E 0872
40200 3A 00 90 3E 32 5E 90 C2 0A63
40208 AF 90 3A 5F 90 32 5E 90 0A83
40216 3A 5F 90 3E 32 5E 90 FE 0114
40224 0F C2 AF 90 30 32 5F 90 802
40230 91 47 10 FE 30 6E 01 1D 0831
40238 AF 32 5E 90 C3 AF 90 3A 0A63
```

```
40240 5B 90 30 32 5B 90 C2 AF 880
40248 90 3A 5A 90 32 5B 90 3A 8110
40256 5F 90 3D 47 5A 5F 90 8B 8E72
40264 CA AF 90 7B 32 5B 90 C1 1047
40272 08 7B 81 C2 8B 9C 09 00 1141
40280 09 0E 00 01 01 01 00 02 051
40288 00 00 FF 80 09 02 01 0A 173
40296 A1 32 4D 3E 32 4D 41 32 0A55
40304 4D 4F 32 4D FF 00 7E 01 0779
40312 9A 01 57 4D 83 FF 00 9A 0E72
40320 FA 00 0F 3F 42 83 FF 40 932
40328 0F 04 01 0A 52 5D 7C 4A 0784
40336 50 7C 3E 5D 7C 46 5D 7C 783
40344 5D 7C 65 5D 7C 6E 5D 7C 0E71
40352 7C 63 53 6E 53 7C 7E 0E71
40360 53 7C 8C 53 7C 53 7C 8E5
40368 AF 53 7C 53 7C 53 FF 40 0799
40376 09 04 01 0A 64 85 0B 39 0544
40384 C0 70 9A C8 8A 9E 6A 1180
40392 54 85 C8 5F 85 08 6A 85 1072
40400 C0 70 9A C8 8A 9E 6A 1180
40408 9A 81 5F 9A 81 4A 9A 81 1320
40416 71 9A 81 7F 97 81 71 9A 1254
40424 A1 4A 9A 81 4E 90 8B 1254
40432 90 8E 4E 90 8E 4E 90 8B 1170
40440 4A 9C 8E 5B 9C 8E 4E 9D 1170
40448 8B 5B 90 8E 4E 90 8B 63 1194
40456 90 8E 4F 90 8A 90 8B 1418
40464 7A 90 8E 7A 90 8B 7A 9D 1295
40472 8E 7A 90 8E 3B 83 7B 1219
40480 53 C4 2F 41 C2 37 37 C2 0A67
40488 3B 83 7B 3B 53 C4 2F 41 902
40496 C2 37 37 C3 63 57 35 0798
40504 53 C4 2F 41 C2 37 37 C2 0909
40512 53 C4 2F 41 C2 37 C3 63 57 0893
40520 C3 53 37 C3 63 53 0F 63 1090
40528 5F 43 5F 43 5F 43 5F 1097
40536 53 63 5F 43 5F 43 5F 1010
40544 5F 43 5F 43 5F 43 5F 1010
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40560 5F 43 5F 43 5F 43 5F 1010
40568 5F 43 5F 43 5F 43 5F 1010
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40608 9A 43 7B 4A 0F 70 3E 0F 1149
40616 0F 9A 3E 9F 8A 0F 07 0A 1216
40624 73 C4 8A 41 C7 8A 37 C3 1007
40632 AF 83 C7 AF 83 C6 AF 41 0777
40640 C5 AF 37 C3 C6 AF 83 C7 1004
40648 53 C6 83 41 C5 83 37 C3 0991
40656 83 43 37 C3 C6 83 41 1040
40664 53 C6 83 41 C5 83 37 C3 0991
40672 53 C6 83 41 C5 83 37 C3 0991
40680 83 43 37 C3 C6 83 41 1040
40688 C3 3E 37 C3 30 02 7F 1054
40696 7A 8B 4D 82 8C 45 CF 3A 00 1020
40704 3D 5B 52 7A 8B 82 8C 45 0772
40712 CF 5B 5A 80 5D 80 02 77 1074
```

```
40720 5B 02 5C 45 CF 5B 3A 80 1020
40728 20 5D 82 7A 5B 20 5C 45 0528
40736 8B 5B 3A 8B 53 45 8C 45 0943
40744 3E 0E 43 4D 42 42 3E 0E 1090
40752 63 63 0E 63 5E 0E 63 4A 1009
40760 AF 62 3E 0E 63 63 9A 63 0936
40768 5E 7B 43 4D 42 42 3E 7A 1071
40776 A3 63 7B 43 5E 7B 43 4A 1040
40784 7B 43 5E 7B 43 5E 7B 43 1017
40792 01 00 A3 63 7B 43 5E 7B 0901
40800 A3 63 7B 43 5E 7B 43 5E 1027
40808 7B 43 5E 7B 43 4A 7B 62 1208
40816 3E 7B 43 5E 7B 43 5E 7B 1223
40824 AF 4A 7B 43 5E 7B 43 5E 1044
40832 7B 43 5E 7B 43 4A 7B 43 1240
40840 3E 7B 43 5E 7B 43 5E 7B 1240
40848 4A 59 5C 53 63 5C 59 AF 0987
40856 8E 31 63 5C 63 7C 7F 9A 1188
40864 4F 60 09 01 00 00 57 8A 0864
40872 63 4B 4B 53 53 4B 53 42 934
40880 63 4B 4B 53 4B 53 4B 53 940
40888 42 AF 9A 4F 9A 4F 9A 4F 9064
40896 9A 5B AF 9A 4F 9A 4F 9A 1013
40904 4F 9A 5B AF 9A 4F 9A 4F 9A 1013
40912 4F 9A 5B AF 9A 4F 9A 4F 9A 1013
40920 83 4B 63 2A 83 4B 63 907
40928 83 4B 63 2A 83 4B 63 907
40936 AF 9A 9A AF 9A 7A AF 9A 1043
40944 AF 9A 9A AF 9A 7A AF 9A 1128
40952 09 01 1E 01 AF 9A 8E AF 833
40960 9A 8E AF 9A 8E AF 9A 8E 1332
40968 73 8A 8E AF 9A 8E 7D 8A 1262
40976 8E AF 9A 8E 50 8C 8E AF 1264
40984 8E AF 9A 8E AF 9A 8E AF 1308
40992 7D 8C 8E AF 9A 8E 50 8C 1193
41000 8E AF 9A 8E 50 7D 8C 8E 1223
41008 7C 8E 7C 7C 8E 9C 7C 8E 1311
41016 7C 7C 8E 83 7C 8E 7C 1122
41024 0C 5D 7C 8E 41 7C 8E 7C 1250
41032 7C 8E 4F 5E 8F 8E 8E 1374
41040 4F 5E 8F 8E 4F 5E 8F 8E 1221
41048 AF 5E 8F 8E 4F 5E 8F 8E 1242
41056 AF 5E 8F 8E 4F 5E 8F 8E 1242
41064 01 5D 5D 0E 01 5D 0E 1120
41072 0F 40 0F 40 0F 40 0F 1200
41080 7C 93 63 63 63 63 63 1621
41088 8D 7C 93 63 63 63 63 1688
41096 8D 7C 93 63 63 63 63 1530
41104 8D 25 01 00 1E 82 7C 93 0851
41112 0F 40 0F 01 00 02 7C 9A 0840
41120 8D 9C 4E 8E 8F 9A 8B 3A 0800
41128 6D 83 2B 41 83 41 83 41 0510
41136 3D 7A 8B 43 4E 8B 4F 7A 0725
41144 8B 43 4E 8B 43 4E 8B 43 0725
41152 4D 0F 01 01 01 01 00 7B 0796
41160 8E 8E 8E 8E 8E 8E 8E 1791
41168 0F 40 0F 3E 7C 93 03 0A 3A
41176 01 82 80 11 82 80 7C 93 1490
41184 03 12 82 80 11 82 80 7C 1547
41192 93 03 12 82 80 7C 93 1243
41200 00 1E 82 80 7C 93 0F 711
41208 01 00 02 02 7A 8B 43 4E 0849
41216 8B 43 4E 8B 43 4E 8B 43 0854
41224 83 43 41 4D 43 45 8A 0F 1011
41232 8E 8E 8E 8E 8E 8E 8E 1022
41240 8E 8E 8E 8E 8E 8E 8E 1004
41248 9C 8A 8E 8A 9C 9C 9C 1338
41256 4E 8E 8E 8E 8E 8E 8E 1048
41264 90 7B 8B 43 4E 8B 43 1013
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41280 41 4B 43 50 40 90 3A 5E 7A65
41288 90 3A 5E 90 3A 5E 90 3A 7121
41296 40 90 3A 5E 90 3A 5E 90 421
41304 90 3A 5E 90 3A 5E 90 3A 7073
41312 90 3A 5E 90 3A 5E 90 3A 7073
41320 40 90 3A 5E 90 3A 5E 90 421
41328 3A 90 3E 00 90 3A 5E 90 881
41336 01 39 40 00 00 00 00 0298
STOP
```

# Chronos

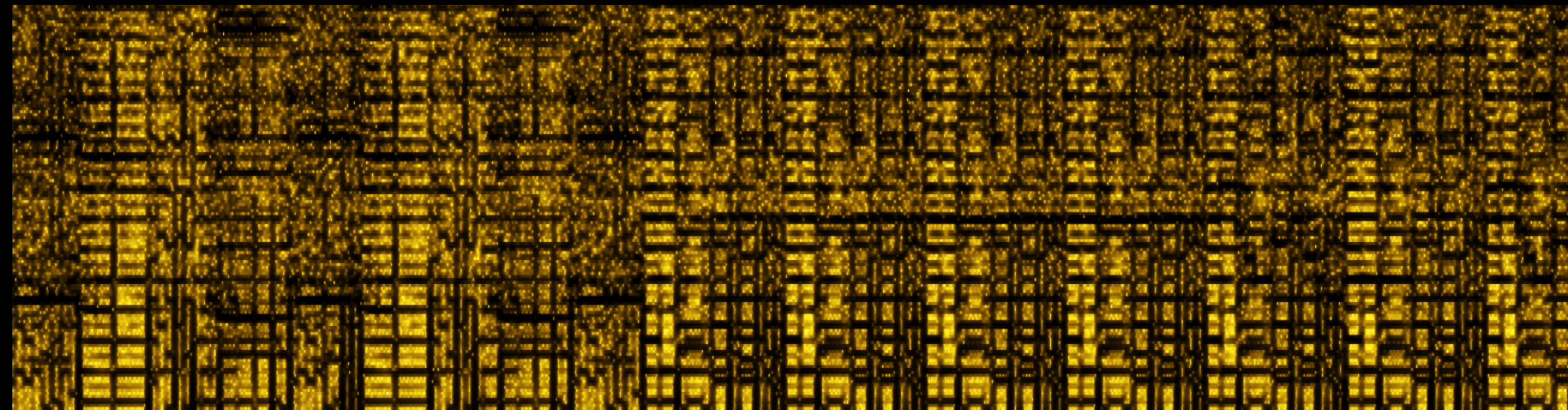
- Tim Follin, 1987
- Code turns ZX Spectrum beeper on and off fast
- Clicks



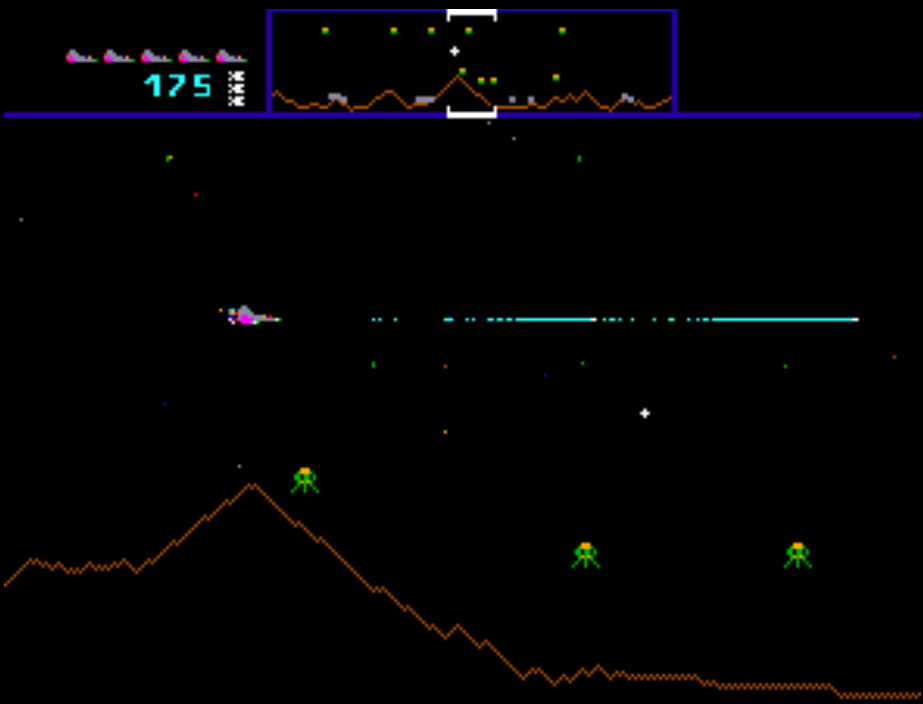


# What We Hear

- Multiple sound channels!
- Different instrument types!
- Complex structure!
- Also: Noisy as hell



Next Game



# Game Sound Before Defender

Galaxian (1979)

Asteroids (1979)



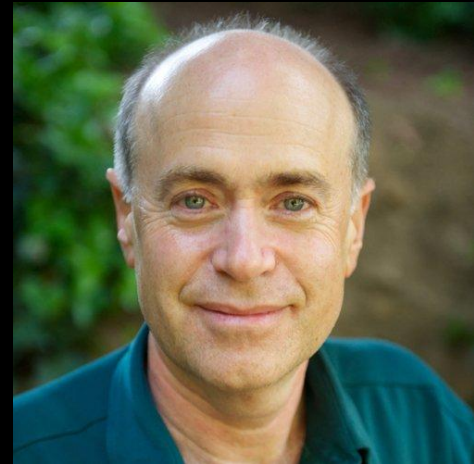
# Defender Gameplay

# Defender

1980 Williams Electronics

Audio implementation:

- Eugene Jarvis
- Sam Dicker



# GWave

Eugene Jarvis

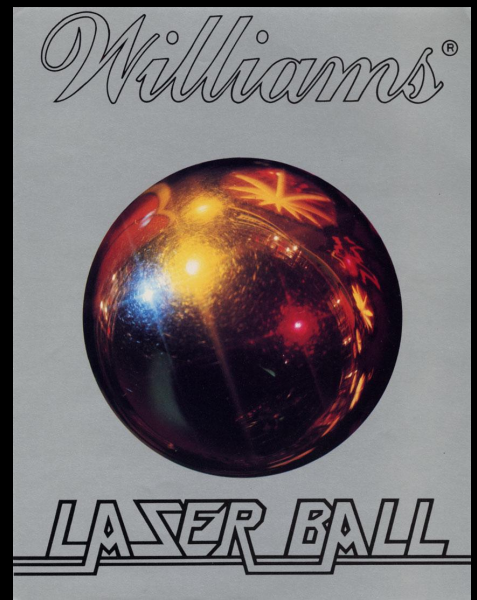
- created for 'Laser Ball' pinball (1979)

Basic synth code:

- wave tables
- frequency tables
- white noise

Effects:

- echo, distortion, LFOs



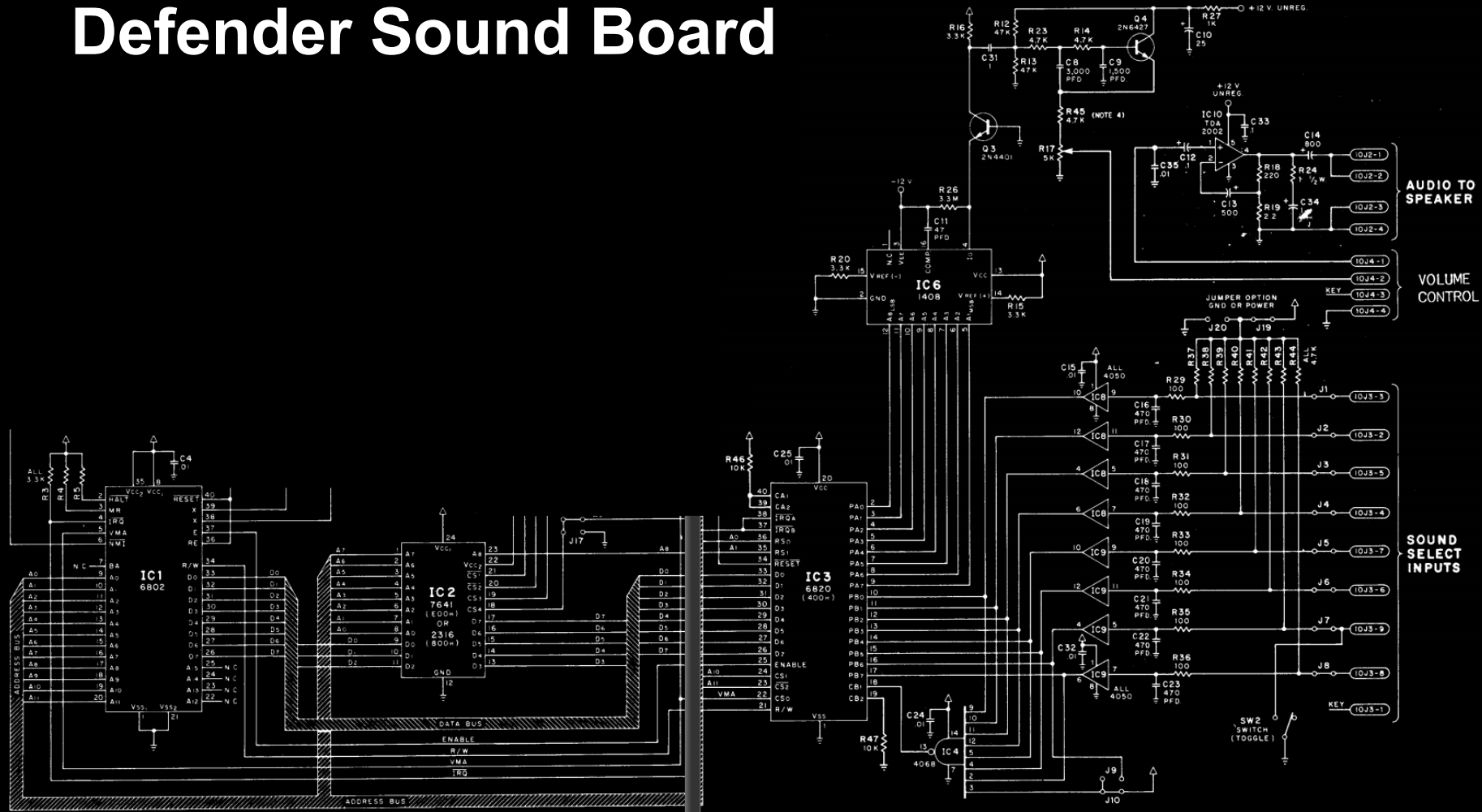
**Warning!**

**Nerdy stuff ahead**





# Defender Sound Board





# Defender Sound Board

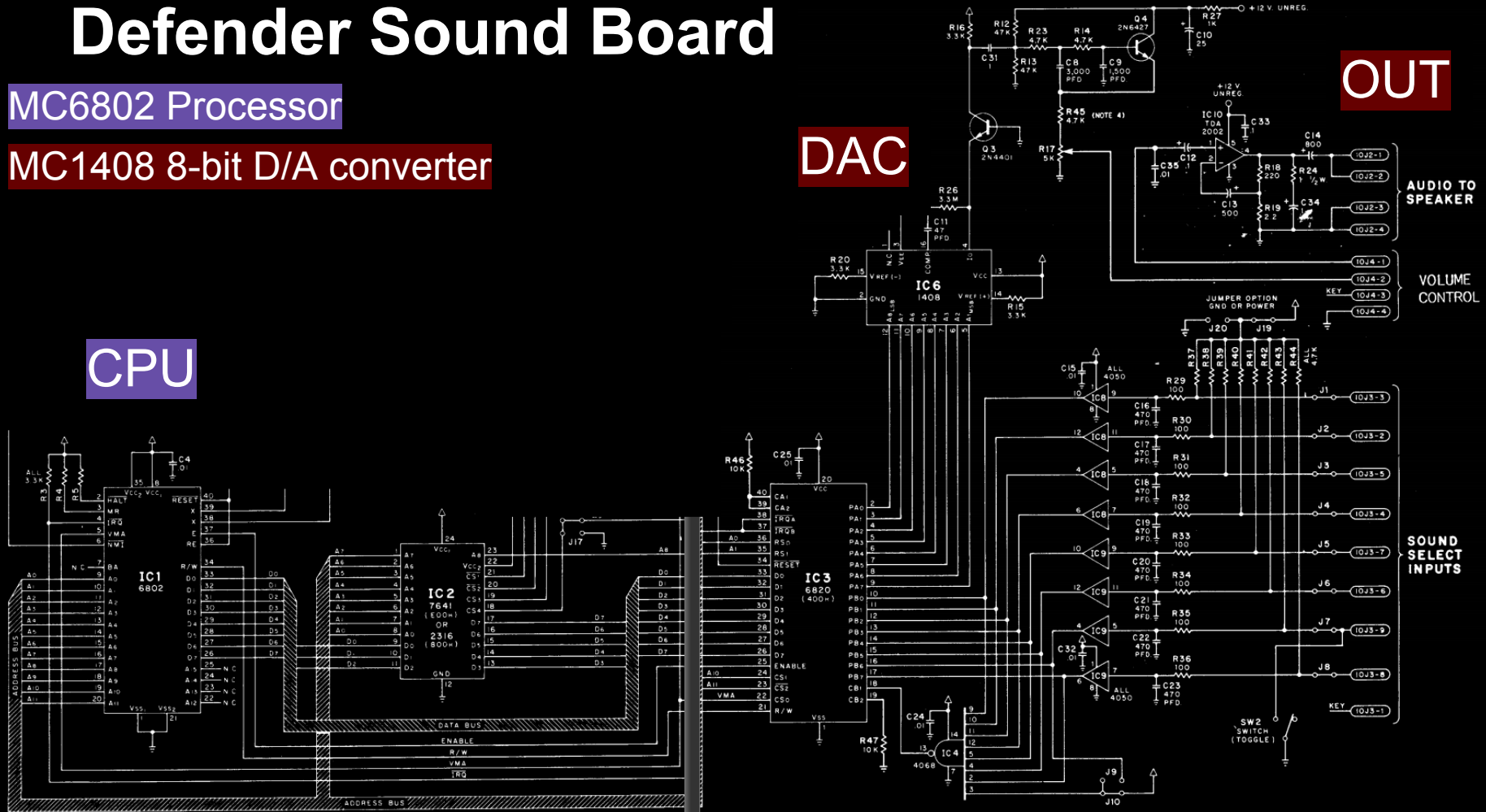
MC6802 Processor

MC1408 8-bit D/A converter

CPU

DAC

OUT



# Defender Sound Board

MC6802 Processor

MC1408 8-bit D/A converter

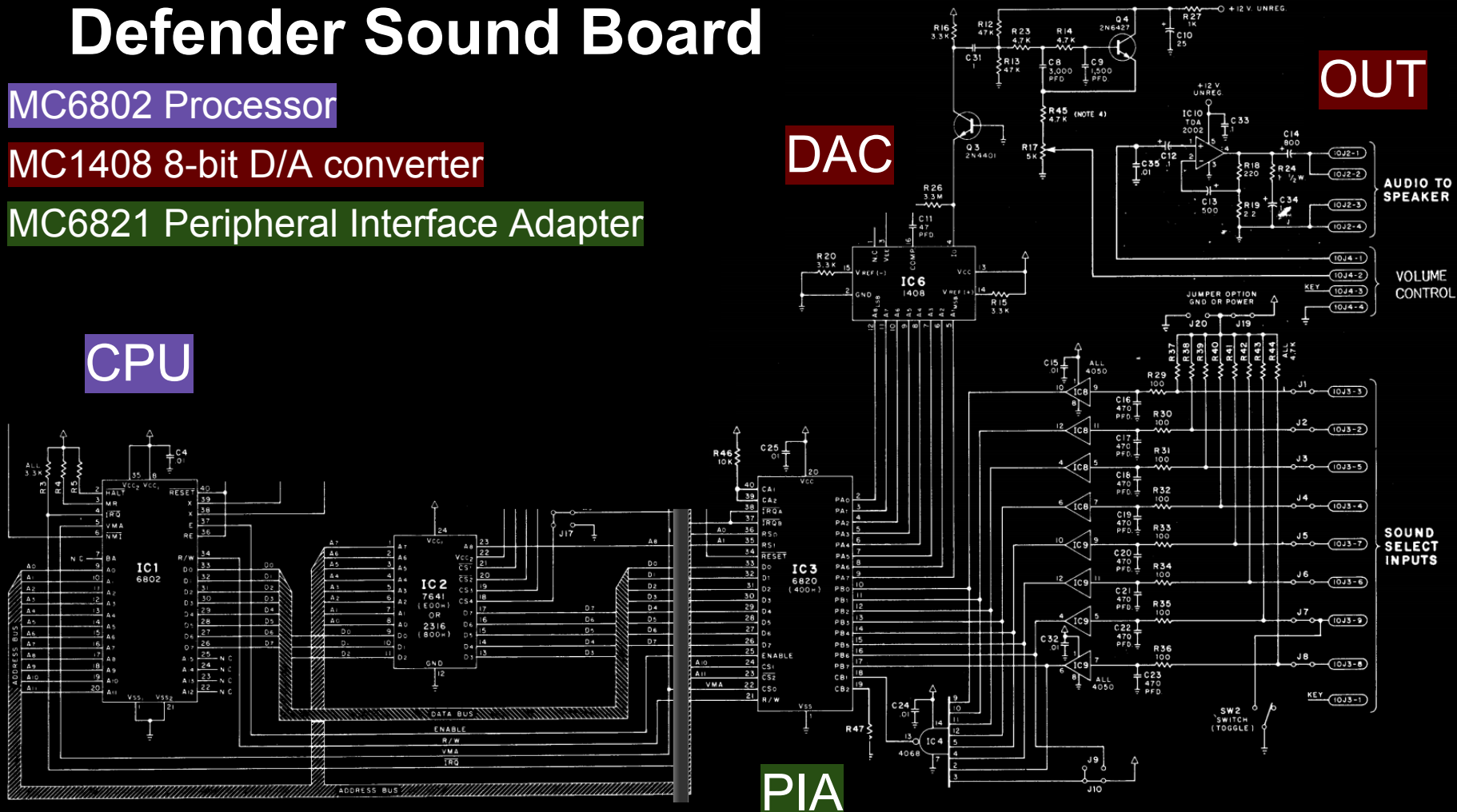
MC6821 Peripheral Interface Adapter

CPU

DAC

PIA

OUT



# Defender Sound Board

MC6802 Processor

MC1408 8-bit D/A converter

MC6821 Peripheral Interface Adapter

Harris 7641 PROM: 2048 bytes

CPU

ROM

DAC

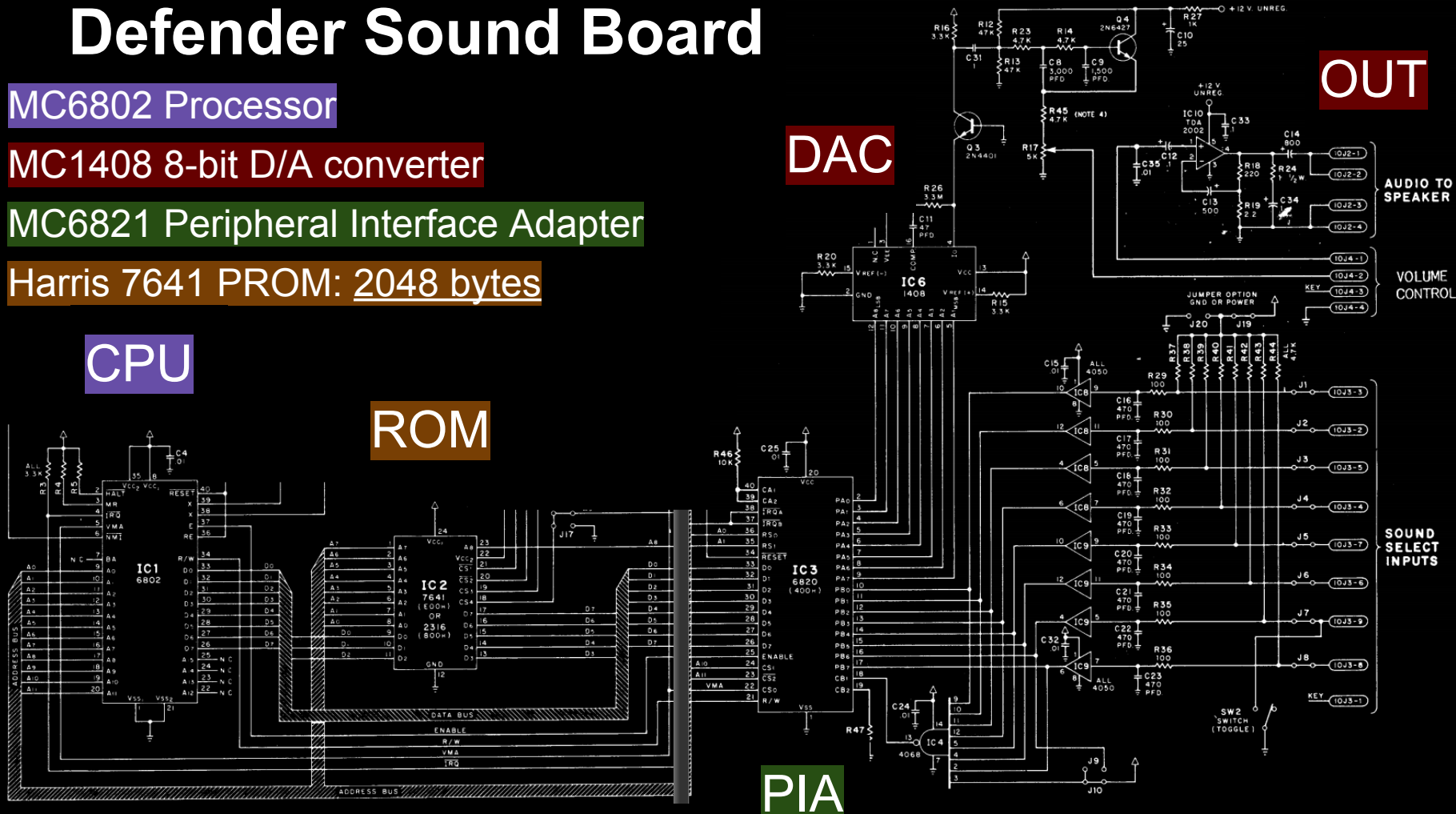
OUT

AUDIO TO SPEAKER

VOLUME CONTROL

SOUND SELECT INPUTS

PIA



# Defender Sound ROM

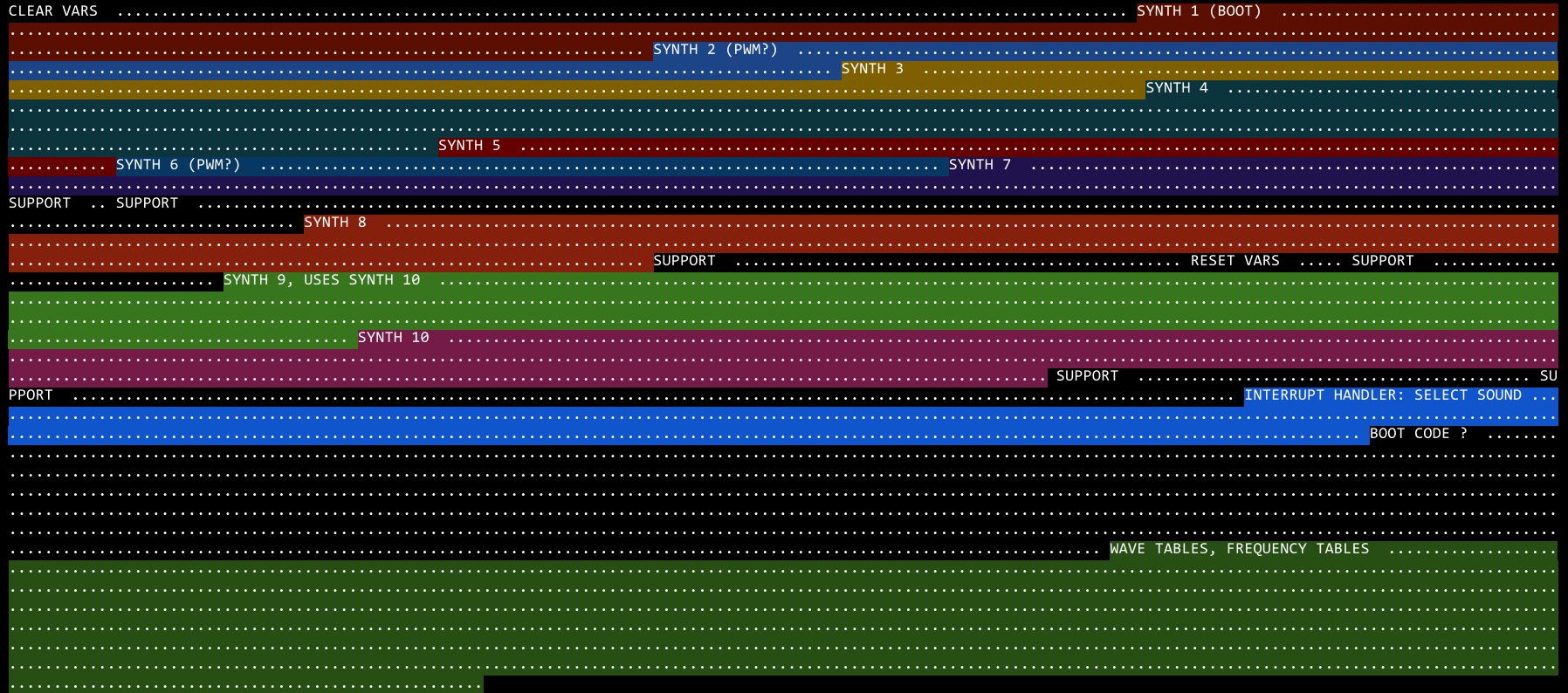
2048 bytes for all Defender audio



# Defender Sound ROM, 2048 bytes

```
FF 0F 8E 00 7F CE 04 00 6F 01 6F 03 86 FF A7 00 6F 02 86 37 A7 03 86 3C A7 01 97 09 4F 97 07 97 04 97 05 97 06 97 07 08 0E 20 FE 16 48 48 48 1B CE 00 13 DF 0F CE FD 76 BD
FD 21 C6 09 7E FB 0A 96 1B B7 04 00 96 13 97 1C 96 14 97 1D DE 18 96 1C 73 04 00 09 27 10 4A 26 FA 73 04 00 96 1D 09 27 05 4A 26 FA 20 E8 B6 04 00 2B 01 43 8B 00 B7 04
00 96 1C 9B 15 97 1C 96 1D 9B 16 97 1D 91 26 CB 96 1A 27 06 9B 13 97 13 26 B9 39 86 01 97 1A C6 03 20 0A 86 FE 97 1A 86 C0 C6 10 20 00 97 19 86 FF B7 04 00 D7 15 D6
15 96 0A 44 44 44 98 0A 44 76 00 09 76 00 0A 24 03 73 04 00 96 19 4A 26 FD 5A 26 E5 96 19 9B 1A 97 19 26 DB 39 86 20 97 15 97 18 86 01 CE 00 01 C6 FF 20 00 97 13 DF 16
D7 14 D6 15 96 0A 44 44 44 98 0A 44 76 00 09 76 00 0A 86 00 24 02 96 14 B7 04 00 DE 16 09 26 FD 5A 26 E1 D6 14 D0 13 27 09 DE 16 08 96 18 27 D0 20 CC 39 C6 01 D7 04 4F
97 19 20 14 4F 97 19 C6 03 20 0D 86 01 97 19 CE 03 E8 86 01 C6 FF 20 00 97 18 D7 13 DF 16 7F 00 15 DE 16 B6 04 00 16 54 54 D8 0A 54 76 00 09 76 00 0A D6 13 7D 00 19
27 02 D4 09 D7 14 D6 15 91 0A 22 12 09 27 26 B7 04 00 DB 15 99 14 25 16 91 0A 23 F0 20 10 09 27 14 B7 04 00 D0 15 92 14 25 04 91 0A 22 F0 96 0A B7 04 00 20 B9 06 18 27
B5 96 13 D6 15 44 56 44 56 44 56 43 50 82 FF DB 15 99 13 D7 15 97 13 26 98 C1 07 26 94 39 86 FD 97 0F CE 00 64 DF 0B DB 0C 96 11 99 0B 97 11 DE 0B 25 04 20 00 20 03 08
27 11 DF 0B 84 0F 8B 9A 97 10 DE 0F A6 00 B7 04 00 20 DC 39 4F B7 04 00 97 11 4F 91 11 26 03 73 04 00 C6 12 5A 26 FD 4C 2A F1 73 04 00 7C 00 11 2A E8 39 CE 00 13 6F 00
08 8C 00 1B 26 F8 86 40 97 13 CE 00 13 86 80 97 11 5F A6 01 AB 00 A7 01 2A 02 DB 11 74 00 11 08 08 8C 00 1B 26 EC F7 04 00 7C 00 12 26 DC CE 00 13 5F A6 00 27 0B 81 37
26 04 C6 41 E7 02 6A 00 5C 08 08 8C 00 1B 26 EA 5D 26 BF 39 7A 00 08 39 7F 00 08 97 11 CE FD AA A6 00 27 2D 7A 00 11 27 06 4C BD FD 21 20 F1 08 DF 0F BD FD 21 DF 0D DE
0F A6 00 97 15 A6 01 EE 02 DF 13 8D 3E DE 0F 08 08 08 08 DF 0F 9C 0D 26 E8 7E FD 0E 86 03 97 08 39 7A 00 08 27 0C D6 15 58 58 58 58 1B 97 15 4F 20 FE 4A 81 0B 23 01 4F
CE FE 41 BD FD 21 A6 00 CE FF FF DF 13 8D 04 8D 2A 20 FC CE 00 16 81 00 27 15 81 03 27 09 C6 01 E7 00 08 80 02 20 EF C6 91 E7 00 6F 01 08 08 C6 7E E7 00 C6 FA E7 01 C6
DD E7 02 DE 13 4F F6 00 12 5C D7 12 D4 15 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 1B 48 48 48 48 B7 04 00 09 27 03 7E 00 16 39 36 A6 00 DF 0D DE
0F A7 00 08 DF 0F DE 0D 08 5A 26 EF 32 39 4F 97 04 97 05 39 7F 00 04 96 05 84 7F 81 1D 26 01 4F 4C 97 05 39 86 0E BD FB 81 96 05 48 48 43 BD FC 39 7C 00 17 BD FC 3B 20
F8 86 03 BD F8 2A D6 06 C1 1F 26 01 5F 5C D7 06 86 20 10 5F 81 14 23 05 CB 0E 4A 20 F7 CB 05 4A 26 FB D7 13 BD F8 3F 20 FB 96 07 26 09 7C 00 07 86 0D 08 05 20 69 7E FC
2E 16 58 1B 1B 1B CE FE EC BD FD 21 A6 00 16 84 0F 97 14 54 54 54 54 D7 13 A6 01 16 54 54 54 D7 15 84 0F 97 11 DF 0B CE FE 4D 7A 00 11 2B 08 A6 00 4C BD FD 21 20 F3
DF 18 BD FC 75 DE 0B A6 02 97 1A BD FC 87 DE 0B A6 03 97 16 A6 04 97 1F A6 05 16 A6 06 CE FF 55 BD FD 21 17 DF 1B 7F 00 23 BD FD 21 DF 1D 39 96 13 97 22 DE 1B DF 0D DE
0D A6 00 9B 23 97 21 9C 1D 27 26 D6 14 08 DF 0E CE 24 96 21 4A 26 FD A6 00 B7 04 00 08 9C 1F 26 F1 5A 27 DA 08 09 08 09 08 09 08 09 01 01 20 DF 96 15 8D 62 7A 00 22
26 C1 96 07 26 46 96 16 27 42 7A 00 17 27 3D 9B 23 97 23 DE 1B 5F 96 23 70 00 16 2B 06 AB 00 25 08 20 0B AB 00 27 02 25 05 5D 27 08 20 0F 5D 26 03 DF 1B 5C 08 9C 1D 26
DD 5D 26 01 39 DF 1D 96 15 27 06 8D 08 96 1A 8D 16 7E FB E7 39 CE 00 24 DF 0F DE 18 E6 00 08 BD FB 0A DE 0F DF 1F 39 4D 27 2B DE 18 DF 0D CE 00 24 97 12 DF 0F DE 0D D6
12 D7 11 E6 01 54 54 54 54 08 DF 0D DE 0F A6 00 10 7A 00 11 26 FA 27 04 80 08 9C 1F 26 DE 39 8E 00 7F B6 04 02 0E 43 84 1F D6 08 27 09 2A 03 BD FA 48 4A BD FA 89 5F 81 0E
27 02 D7 06 81 12 27 02 D7 07 F6 EF DC 1 7E 26 03 BD EF DD 4D 27 27 4A 81 0C 22 08 BD FB 81 BD FB E7 20 1A 81 1B 22 0E 80 0D 48 CE FD 58 8D 21 EE 0A AD 00 20 08 80 1C
BD F8 2A BD F8 3F 96 04 9A 05 27 FE 4F 97 07 96 04 27 03 7E F9 13 7E FB 34 DF 0D 9B 0E 97 0E 24 03 7C 00 0D DE 0D 39 0F 8E 00 7F CE FF FF 5F E9 00 09 8C F8 00 26 F8 E1
00 27 01 3E 86 01 BD F8 2A BD F8 3F F6 EF FA C1 7E 26 DC BD EF FA 20 D7 FB 49 F9 13 FB 24 F8 8C FB 1F FB 1E F8 C DF F8 94 F9 1 C F9 23 F9 A6 F9 D4 F9 F3 FA 44 FA 84 40 7F
00 10 E1 00 80 FF FF 28 01 00 08 81 02 00 FF FF 28 81 00 FC 01 02 00 FC FF FF 01 00 18 41 04 80 00 FF 8C 5B B6 40 BF 49 A4 73 73 A4 49 BF 40 B6 58 8C 0C 7F 1D 0F FB 7F
23 0F 15 FE 08 50 8B 88 3E 3F 02 3E 7C 04 03 FF 3F 2C E2 7C 12 0D 74 7C 0D 0E 41 7C 23 0B 50 7C 1D 29 F2 7C 3F 02 3E F8 04 03 FF 7C 2C E2 F8 12 0D 74 F8 0D 0E 41
F8 23 0B 50 F8 1D 2F F2 F8 23 05 A8 08 12 06 BA F8 04 07 FF 7C 37 04 C1 7C 23 05 A8 7C 12 06 BA 3E 04 07 FF 3E 37 04 C1 3E 23 05 A8 1F 12 06 BA 1F 04 07 FF 1F 37 04 C1
1F 23 16 A0 FE 1D 17 F9 7F 37 10 7F B0 D9 F5 FF F5 D9 B0 7F 4E 24 09 0F 09 24 4E 10 7F C5 EC E7 BF 8D 6D 6A 7F 94 92 71 40 17 12 39 10 FF FF FF 00 00 00 FF FF FF 00 00
40 80 00 FF 00 80 40 10 7F B0 D9 F5 FF F5 D9 B0 7F 4E 24 09 0F 09 24 4E 10 7F C5 EC E7 BF 8D 6D 6A 7F 94 92 71 40 17 12 39 10 FF FF FF 00 00 00 FF FF FF 00 00
00 00 48 8A 95 A0 AB B5 BF C8 D1 DA E1 E8 EE F3 F7 FB FD FE FF FE FD FB F7 F3 EE E8 E1 DA D1 C8 BF B5 AB A0 95 8A 7F 6A 5F 54 4A 40 37 2E 25 1E 17 11 0C 08 04 02 01
00 01 02 04 08 0C 11 17 1E 25 2E 37 40 4A 54 5F 6A 75 7F 10 59 7B 98 AC B3 AC 98 7B 59 37 19 06 00 16 37 81 24 00 00 00 16 31 12 05 1A FF 00 27 6D 11 05 11 01 02 01
47 11 31 00 01 00 0D 1B F4 12 00 00 00 14 47 41 45 00 00 0F 5B 21 35 11 FF 00 0D 1B 15 00 FD 00 01 69 31 11 00 01 00 03 6A 01 15 01 01 01 47 F6 53 03 00 02 06
94 6A 10 02 00 02 06 9A 1F 12 00 FF 10 04 69 31 11 00 FF 00 0D 00 12 06 00 FF 01 09 28 A0 98 90 88 80 78 70 68 60 58 50 44 40 01 01 02 02 04 04 08 08 10 10 30 60 C0 E0
01 01 02 02 03 04 05 06 07 08 09 0A 0C 80 7C 78 74 70 74 78 7C 80 01 01 02 02 04 08 08 10 20 28 30 38 40 48 50 60 70 80 A0 B0 C0 08 40 08 40 08 40 08 40 08 40 08 40
08 40 08 40 08 40 08 01 02 04 08 09 0A 0C 0E 0F 10 12 14 16 40 10 08 01 01 01 01 01 02 02 03 03 04 04 05 06 08 0A 0C 10 14 18 20 30 40 50 40 30 20 10 0C 0A 08 07
06 05 04 03 02 02 01 01 01 07 08 09 0A 0C 08 17 18 19 1A 1B 1C 00 00 00 FC B6 F8 01 FD 2F F8 01
```

# Defender Sound ROM Map

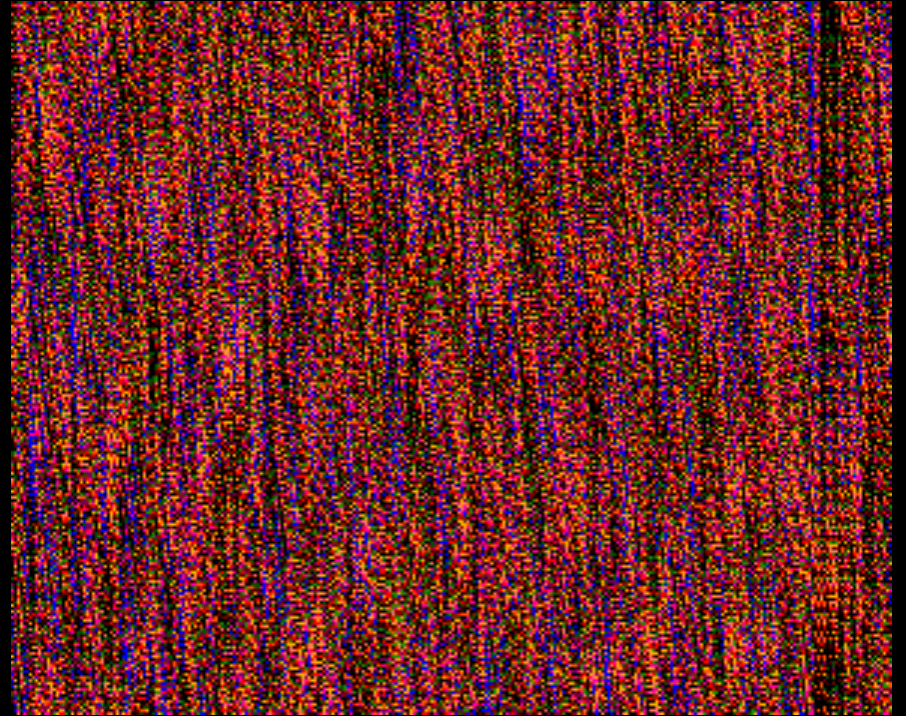




# Defender Boot Sound

Recording is 48 KHz, 16 bit mono

255,014 bytes



# Defender Boot Sound, 98 bytes

```
FF 0F 8E 00 7F CE 04 00 6F 01 6F 03 86 FF A7 00 6F 02 86 37 A7 03 86 3C A7 01 97 09 4F 97 07 97 04 97 05 97 06 97 07 08 0E 20 FE 16 48 48 48 1B CE 00 13 DF 0F CE FD 76 BD
FD 21 C6 09 7E FB 0A 96 1B B7 04 00 96 13 97 1C 96 14 97 1D DE 18 96 1C 73 04 00 09 27 10 4A 26 FA 73 04 00 96 1D 09 27 05 4A 26 FA 20 E8 B6 04 00 2B 01 43 8B 00 B7 04
00 96 1C 9B 15 97 1C 96 1D 9B 16 97 1D 91 17 26 CB 96 1A 27 06 9B 13 97 13 26 B9 39 86 01 97 1A C6 03 20 0A 86 FE 97 1A 86 C0 C6 10 20 00 97 19 86 FF B7 04 00 D7 15 D6
15 96 0A 44 44 44 98 0A 44 76 00 09 76 00 0A 24 03 73 04 00 96 19 4A 26 FD 5A 26 E5 96 19 9B 1A 97 19 26 DB 39 86 20 97 15 97 18 86 01 CE 00 01 C6 FF 20 00 97 13 DF 16
D7 14 D6 15 96 0A 44 44 44 98 0A 44 76 00 09 76 00 0A 86 00 24 02 96 14 B7 04 00 DE 16 09 26 FD 5A 26 E1 D6 14 D0 13 27 09 DE 16 08 96 18 27 D0 20 CC 39 C6 01 D7 04 4F
97 19 20 14 4F 97 19 C6 03 20 0D 86 01 97 19 CE 03 E8 86 01 C6 FF 20 00 97 11 DF 13 DF 16 7F 00 15 DE 16 B6 04 00 16 54 54 54 D8 0A 54 76 00 09 76 00 0A D6 13 7D 00 19
27 02 D4 09 D7 14 D6 15 91 0A 22 12 09 27 26 B7 04 00 DB 15 99 14 25 16 91 0A 23 F0 20 10 09 27 14 B7 04 00 D0 15 92 14 25 04 91 0A 22 F0 96 0A B7 04 00 20 B9 D6 18 27
B5 96 13 D6 15 44 56 44 56 44 56 43 50 82 FF DB 15 99 13 D7 15 97 13 26 98 C1 07 26 94 39 86 FD 97 0F CE 00 64 DF 0B DB 0C 96 11 99 0B 97 11 DE 0B 25 04 20 00 20 03 08
27 11 DF 0B 84 0F 8B 9A 97 10 DE 0F A6 00 B7 04 00 20 DC 39 4F B7 04 00 97 11 4F 91 11 26 03 73 04 00 C6 12 5A 26 FD 4C 2A F1 73 04 00 7C 00 11 2A E8 39 CE 00 13 6F 00
08 8C 00 1B 26 F8 86 40 97 13 CE 00 13 86 80 97 11 5F A6 01 AB 00 A7 01 2A 02 DB 11 74 00 11 08 08 8C 00 1B 26 EC F7 04 00 7C 00 12 26 DC CE 00 13 5F A6 00 27 0B 81 37
26 04 C6 41 E7 02 6A 00 5C 08 08 8C 00 1B 26 EA 5D 26 BF 39 7A 00 08 39 7F 00 08 97 11 CE FD AA A6 00 27 2D 7A 00 11 27 06 4C BD FD 21 20 F1 08 DF 0F BD FD 21 DF 0D DE
0F A6 00 97 15 A6 01 EE 02 DF 13 8D 3E DE 0F 08 08 08 08 DF 0F 9C 0D 26 E8 7E FD 0E 86 03 97 08 39 7A 00 08 27 0C D6 15 58 58 58 1B 97 15 4F 20 FE 4A 81 0B 23 01 4F
CE FE 41 BD FD 21 A6 00 CE FF FF DF 13 8D 04 2A 20 FC CE 00 16 81 00 27 15 81 03 27 09 C6 01 E7 00 08 80 02 20 EF C6 91 E7 00 6F 01 08 08 C6 7E E7 00 C6 FA E7 01 C6
DD E7 02 DE 13 4F F6 00 12 5C D7 12 D4 15 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00 54 89 00
0F A7 00 08 DF 0F DE 0D 08 5A 26 EF 32 39 4F 97 04 97 05 39 7F 00 04 96 05 84 7F 81 1D 26 01 4F 4C 97 05 39 86 0E BD FB 81 96 05 48 48 43 BD FC 39 7C 00 17 BD FC 3B 20
F8 86 03 BD F8 2A D6 06 C1 1F 26 01 5F 5C D7 06 86 20 10 5F 81 14 23 05 CB 0E 4A 20 F7 CB 05 4A 26 FB D7 13 BD FB 3D 20 FB 96 07 26 09 7C 00 07 86 0D 8D 05 20 69 7E FC
2E 16 58 1B 1B 1B CE FE EC BD FD 21 A6 00 16 84 0F 97 14 54 54 54 54 D7 13 A6 01 16 54 54 54 D7 15 84 0F 97 11 DF 0B CE FE 4D 7A 00 11 2B 08 A6 00 4C BD FD 21 20 F3
DF 18 BD FC 75 DE 0B A6 02 97 1A BD FC 87 DE 0B A6 03 97 16 A6 04 97 17 A6 05 16 A6 06 CE FF 55 BD FD 21 17 DF 1B 7F 00 23 BD FD 21 DF 1D 39 96 13 97 22 DE 1B DF 0D DE
0D A6 00 9B 23 97 21 9C 1D 27 26 D6 14 08 DF 0E CE 24 96 21 4A 26 FD A6 00 B7 04 00 08 08 9C 1F 26 F1 5A 27 DA 08 09 08 09 08 09 08 09 01 01 20 DF 96 15 8D 62 7A 00 22
26 C1 96 07 26 46 96 16 27 42 7A 00 17 27 3D 9B 23 97 23 DE 1B 5F 96 23 70 00 16 2B 06 AB 9C 25 08 20 08 AB 00 27 02 25 05 5D 27 08 20 0F 5D 26 03 DF 1B 5C 08 9C 1D 26
DD 5D 26 01 39 DF 1D 96 15 27 06 8D 08 96 1A 8D 16 7E FB E7 39 CE 00 24 DF 0F DE 18 E6 00 08 BD FB 0A DE 0F DF 1F 39 4D 27 2B DE 18 DF 0D CE 00 24 97 12 DF 0F DE 0D D6
12 D7 11 E6 01 54 54 54 54 08 DF 0D DE 0F A6 00 10 7A 00 11 26 FA 27 04 08 08 9C 1F 26 DE 39 8E 00 7F B6 04 02 0E 43 84 1F D6 08 27 09 2A 03 BD FA 48 4A BD FA 89 5F 81 0E
27 02 D7 06 81 12 27 02 D7 07 F6 FE FD C1 7E 26 03 BD EF FD 4D 27 4A 81 0C 22 08 BD FB 81 BD FB E7 20 1A 81 1B 22 0E 80 0D 48 CE FD 58 8D 21 EE 00 AD 00 20 08 80 1C
BD F8 2A BD F8 3F 96 04 9A 05 27 FE 4F 97 07 96 04 27 03 7E F9 13 7E FB 34 DF 0D 9B 0E 97 0E 24 03 7C 00 0D DE 0D 39 0F 8E 00 7F CE FF FF 5F E9 00 09 8C F8 00 26 F8 E1
00 27 01 3E 86 01 BD F8 2A BD F8 3F FE FA C1 7E 26 DC BD EF FA 20 D7 FB 49 F9 13 FB 24 F8 8C FB 71 FB 1E F8 C DF F8 94 F9 1 C F9 23 F9 A6 F9 D4 F9 F3 FA 44 FA 84 40 01
00 10 E1 00 80 FF FF 28 01 00 08 81 02 00 FF FF 28 81 00 FC 01 02 00 FC FF FF 01 00 18 41 04 80 0F 7F 8C 5B B6 40 BF 49 A4 73 73 A4 49 BF 40 B6 5F 8C 0C 7F 1D 0F FB 7F
23 0F 15 FE 08 50 8B 88 3E 3F 02 3E 7C 04 03 FF 3F 2C E2 7C 12 0D 74 7C 0D 0E 41 7C 23 0B 50 7C 1D 29 F2 7C 3F 02 3E F8 04 03 FF 7C 3F 2C E2 F8 12 0D 74 F8 0D 0E 41
F8 23 0B 50 F8 1D 2F F2 F8 23 05 A8 F8 12 06 BA F8 04 07 FF 7C 37 04 C1 7C 23 05 A8 7C 12 06 BA 3E 04 07 FF 3E 37 04 C1 3E 23 05 A8 1F 12 06 BA 1F 04 07 FF 1F 37 04 C1
1F 23 16 A0 FE 1D 17 F9 7F 37 13 06 7F 3F 08 FA FE 04 0F FF FE 0D 0E 41 FE 23 05 A8 7C 12 06 BA 3E 04 07 FF 3E 37 04 C1 3E 23 05 A8 1F 12 06 BA 1F 04 07 FF 1F 37 04 C1
40 80 00 F0 80 40 10 7F B0 D9 F5 FF F5 D9 B0 7F 4E 24 09 00 24 4E 10 7F C5 EC E7 BF 8D 6D 6A 7F 94 92 71 40 17 12 39 10 FF FF FF 00 00 00 FF FF FF FF 00 00
00 00 48 8A 95 A0 AB 15 BF BF C8 D1 DA E1 E8 EE F3 F7 FB FD FE FF FE FD FB F7 F3 EE E8 E1 DA D1 C8 BF B5 AB A0 95 8A 7F 75 6A 5F 54 4A 40 37 2E 25 1E 17 11 0C 08 04 02 01
00 01 02 04 08 01 17 1E 25 2E 37 40 4A 54 5F 6A 75 7F 10 59 7B 98 AC B3 AC 98 78 59 37 19 06 00 16 37 81 24 00 00 00 16 31 12 05 1A FF 00 27 6D 11 05 11 01 0F 01
47 11 31 00 01 00 0D 1B F4 12 00 00 00 14 47 41 45 00 00 0F 5B 21 35 11 FF 00 0D 1B 15 00 FD 00 01 69 31 11 00 01 00 03 6A 01 15 01 01 01 47 F6 53 03 00 02 06
94 6A 10 02 00 02 06 9A 1F 12 00 FF 10 04 69 31 11 00 FF 00 0D 00 12 06 00 FF 01 09 28 A0 98 90 88 80 78 70 68 60 58 50 44 04 01 01 02 02 04 04 08 08 10 10 30 60 C0 E0
01 01 02 02 03 04 05 06 07 08 09 0A 0C 80 7C 78 74 70 74 78 7C 80 01 01 02 02 04 08 08 10 20 28 30 38 40 48 50 60 70 80 A0 B0 C0 08 40 08 40 08 40 08 40 08 40 08 40
08 40 08 40 08 40 08 40 01 02 04 08 09 0A 0C 0E 0F 10 12 14 16 40 10 08 01 01 01 01 01 02 03 03 04 04 05 06 08 0A 0C 10 14 18 20 30 40 50 40 30 20 10 0C 0A 08 07
06 05 04 03 02 02 01 01 01 07 08 09 0A 0C 08 17 18 19 1A 1B 1C 00 00 00 FC B6 F8 01 FD 2F F8 01
```

# Defender Boot Sound

16	48	48	48	1B	CE	00	13	DF	0F	CE	FD	76
BD	FD	21	C6	09	7E	FB	0A	96	1B	B7	04	00
96	13	97	1C	96	14	97	1D	DE	18	96	1C	73
04	00	09	27	10	4A	26	FA	73	04	00	96	1D
09	27	05	4A	26	FA	20	E8	B6	04	00	2B	01
43	8B	00	B7	04	00	96	1C	9B	15	97	1C	96
1D	9B	16	97	1D	91	17	26	CB	96	1A	27	06
9B	13	97	13	26	B9	39	<b>^ MC6802 Machine Code</b>					

# Boot Sound, Disassembled

```
F82A: tab
F82B: asla
F82C: asla
F82D: asla
F82E: aba
F82F: ldx #$0013
F832: stx $0F
F834: ldx #$FD76
F837: jsr $FD21
F83A: ldb #$09
F83C: jmp $FB0A
F83F: lda $1B ; vol (always $FF)
F841: sta $0400 ; DAC output
F844: lda $13
F846: sta $1C
F848: lda $14
F84A: sta $1D
```

```
F84C: ldx $18
F84E: lda $1C
F850: com $0400 ; DAC invert
F853: dex
F854: beq $F866
F856: deca
F857: bne $F853
F859: com $0400 ; DAC invert
F85C: lda $1D
F85E: dex
F85F: beq $F866
F861: deca
F862: bne $F85E
F864: bra $F84E
```

```
F866: lda $0400
F869: bmi $F86C
F86B: coma
F86C: adda #$00 ; dummy?
F86E: sta $0400 ; DAC invert
F871: lda $1C
F873: adda $15
F875: sta $1C
F877: lda $1D
F879: adda $16
F87B: sta $1D
F87D: cmpa $17
F87F: bne $F84C ; restart
F881: lda $1A
F883: beq $F88B
F885: adda $13
F887: sta $13
F889: bne $F844
F88B: rts
```

# Boot Sound Loop

```
lda $1B ; A = volume (always 255)
```

```
sta $0400 ; output A to DAC
```

```
loop:
```

```
com $0400 ; invert DAC output
```

```
; - alternates between 0
```

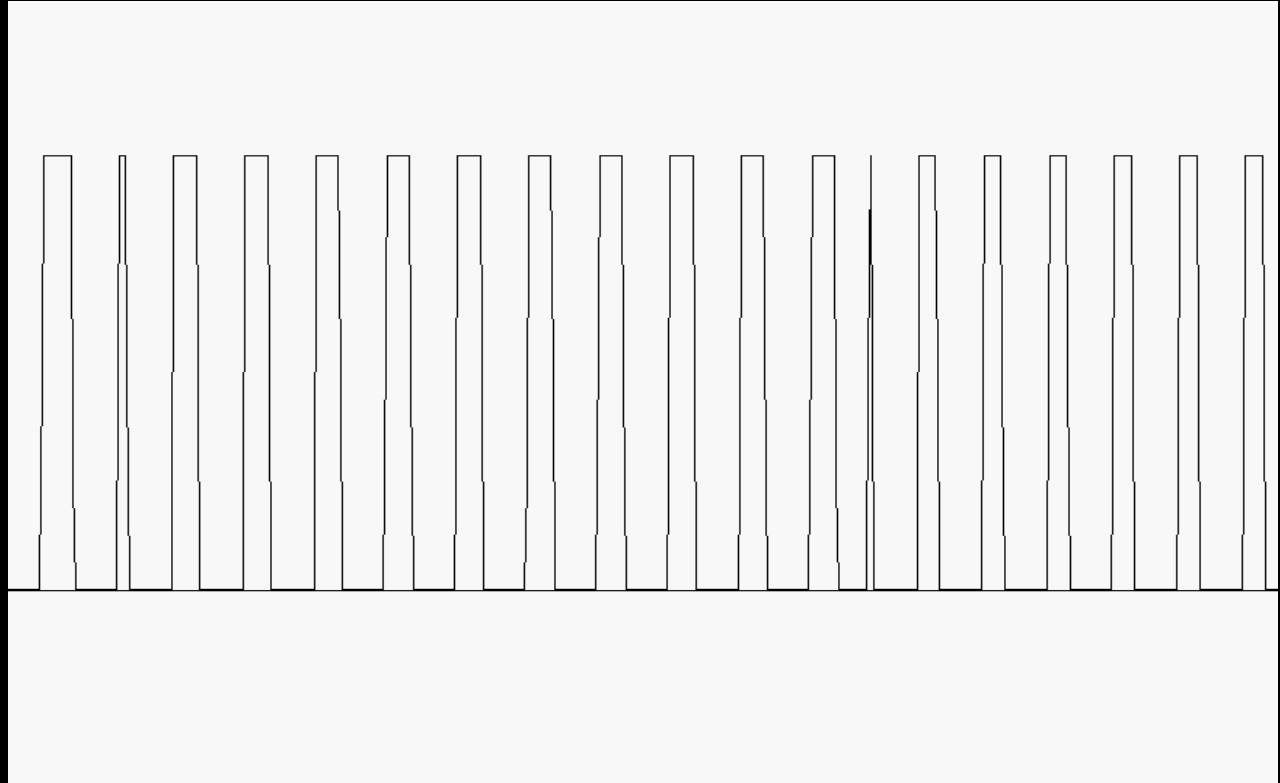
```
; and 255
```

```
... ; variable delay
```

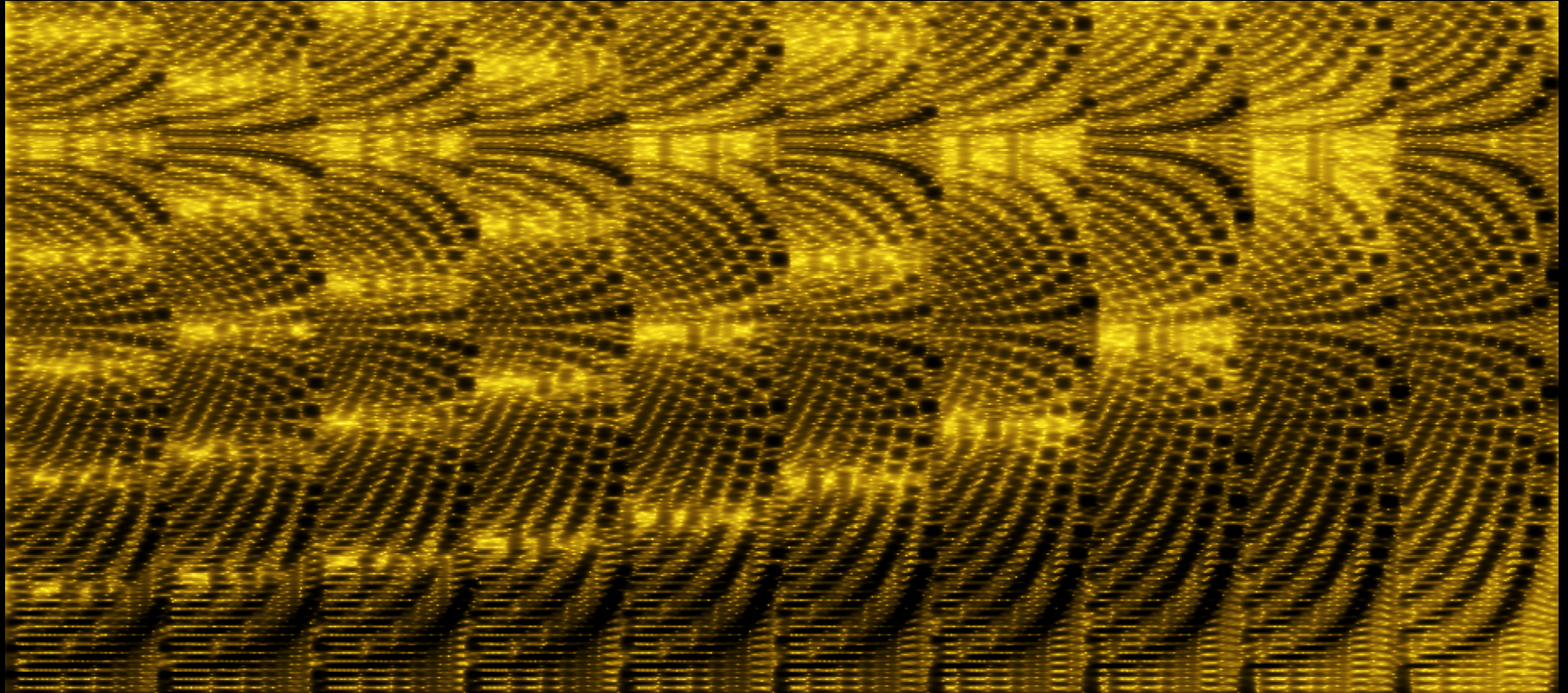
```
bra loop ; goto loop
```

# Defender Boot Sound Output

- Alternates between 0 and 255
- PWM



# What We Hear



# Jarvis About GWave

*I was stunned to find out that the most brilliant sounds were often created by typing in random numbers for the parameters. [...] The crudeness and lack of bounds checking of the program allowed for mathematical wraparound and error accumulation that sounded ethereal.*





# Summary

- Limited hardware
- Unlimited creativity
- Beautiful instruments with FM synthesis
- 1 bit is enough
- Experimentation with parameters yields surprising results

# Modern Audio Synthesis

- Defender audio hardware similar to modern sound cards
- Individual samples are output to a DAC
- Pretty easy to do with modern engines
- Can emulate any other synthesis method
- Why not?

# Audio Synthesis in Unity

```
class Synth : MonoBehaviour {
    float p = 0;
    void OnAudioFilterRead(float[] data, int channels) {
        int smp = 0, length = data.Length;
        while (smp < length) {
            p = (p + 0.002f) % 1;
            float output = Mathf.Sin(p * Mathf.PI * 2) * 0.2f;
            for (int c = 0; c < channels; ++c) data[smp++] = output;
        }
    }
}
```

# Music Synthesis in Unity

```
class SpookyDNBBeat : 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;
        }
    }
}

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;
}

float HH(float p) {
    return Mathf.PerlinNoise(p * 2000, 0f) * (1f - p);
}

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);
}
}
```

## Me:

- [game140.com](http://game140.com)
- [jakob@schmid.dk](mailto:jakob@schmid.dk)
- slides:  
[schmid.dk/spilbar](http://schmid.dk/spilbar)

## Marble Madness:

- Talk: “The making of 1984's Marble Madness”
- Retro Gamer Magazine 53

## Defender:

- [mamedev.org](http://mamedev.org)
- [firepowerpinball.com](http://firepowerpinball.com)  
Eugene Jarvis interview

## 1 bit sound:

- [shiru.untergrund.net/1bit/](http://shiru.untergrund.net/1bit/)

**No more  
slides**



**Extra Slides**



# ULTIMATE Race

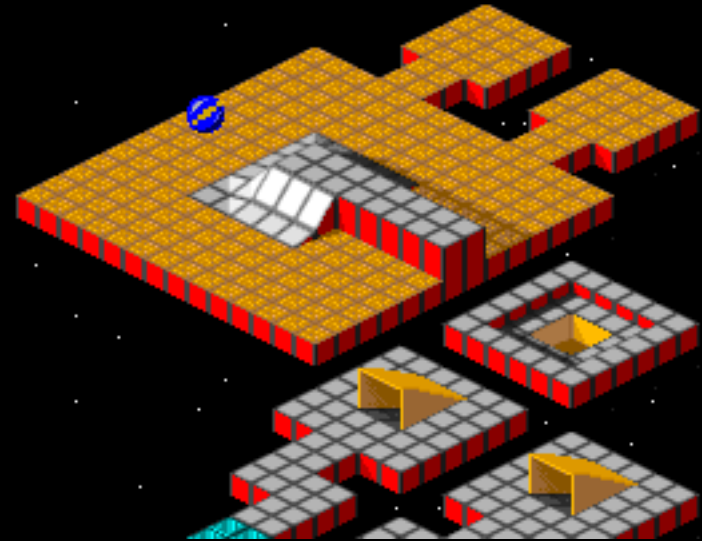
Dynamics

Panning

Tension building

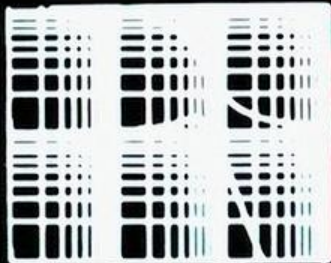
SCORE  
35,170

35



Anticipates game complete music

# Disassemble!



```
INSTALL  
]LOOP  
LDY#10  
LDA VCT.Y  
STA PG3VEC.Y  
DEY  
BPL]LOOP  
LDA $3F3  
EOR #8A5  
STA $3F4
```

and aux mem

```
LDA #PG3VEC/  
LDY #PG3VEC  
STA A1H  
STA A4H  
STY A1L  
STY A4L  
LDA #PG3VEC+10/  
LDY #PG3VEC+10  
STA A2H  
STY A2L  
SEC  
JSR AUXMOVE
```

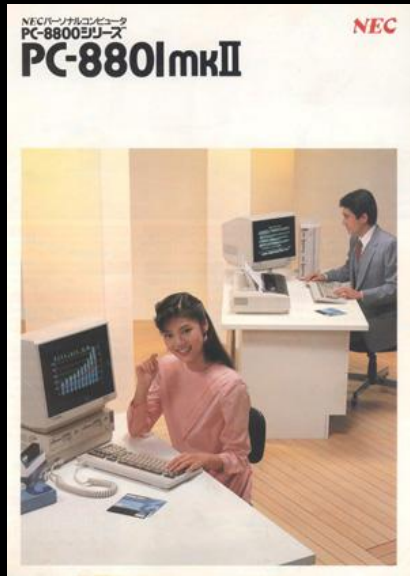
Copy program to aux memory

```
LDA #BEGIN/  
LDY #BEGIN  
STA A1H  
STA A4H  
STY A1L  
STY A4L  
LDA #END/  
LDY #END
```

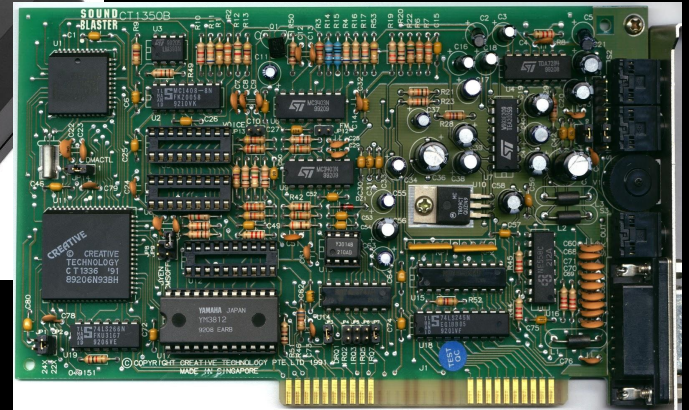
# 1985-89: FM In Your Home

NEC PC-88  
(Japan only)

SEGA Mega Drive /  
Genesis



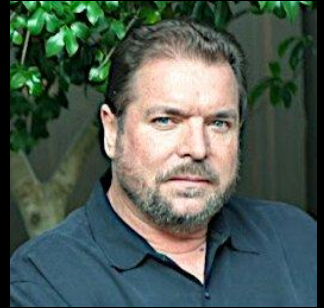
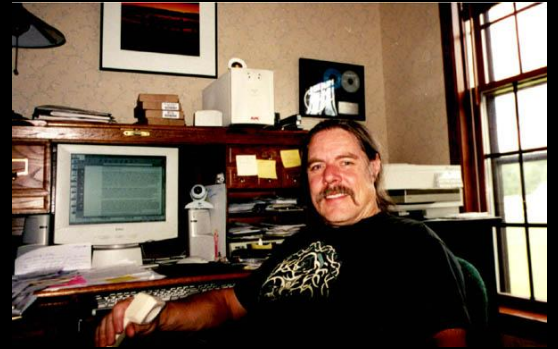
The Sound Blaster



# Atari Music Tools

Marble Madness was composed using  
RPM “Rusty’s Pokey Music”

- by “Rusty” Dawe and Dennis Harper.
- Cross platform (arcade/console)
- Music-V Language, a simple macro language
- Notes was entered in text like “C#8”





PAL



# SILENT HILL

# Akira Yamaoka

Among favourite bands:

Depeche Mode, Vangelis, Hardfloor, Korn, Metallica



# Akira Yamaoka

Konami-dude

Collaborative soundtracks:

Sparkster SNES, 1994

Contra: Hard Corps SEGA Mega Drive/Genesis 1994

(‘Probotector’ in Europe for some reason)



# Silent Hill

Inspired by Angelo Badalamenti

Music is prebaked as audio tracks

Sampler-based  
according to [silenthillforum.com](http://silenthillforum.com),  
he uses a lot of sample CDs

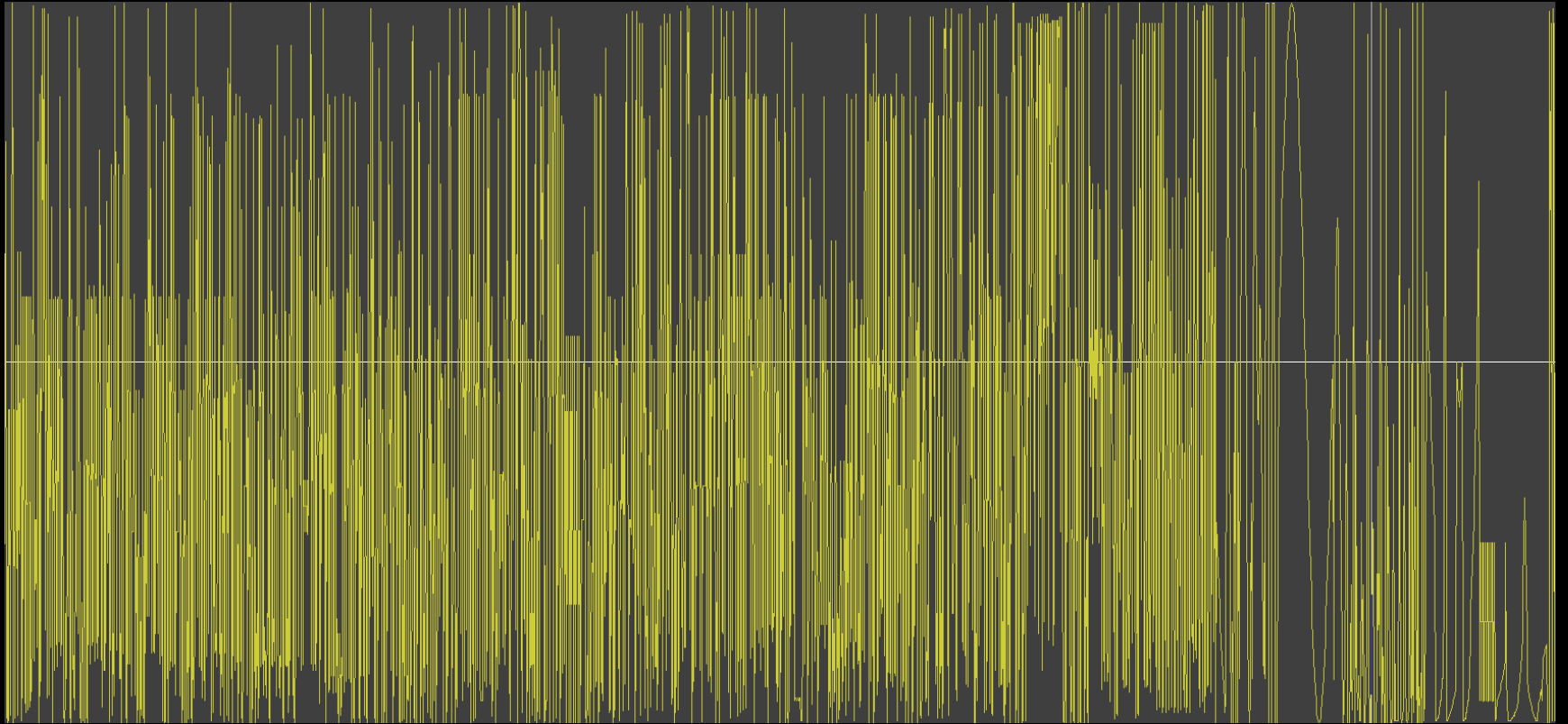








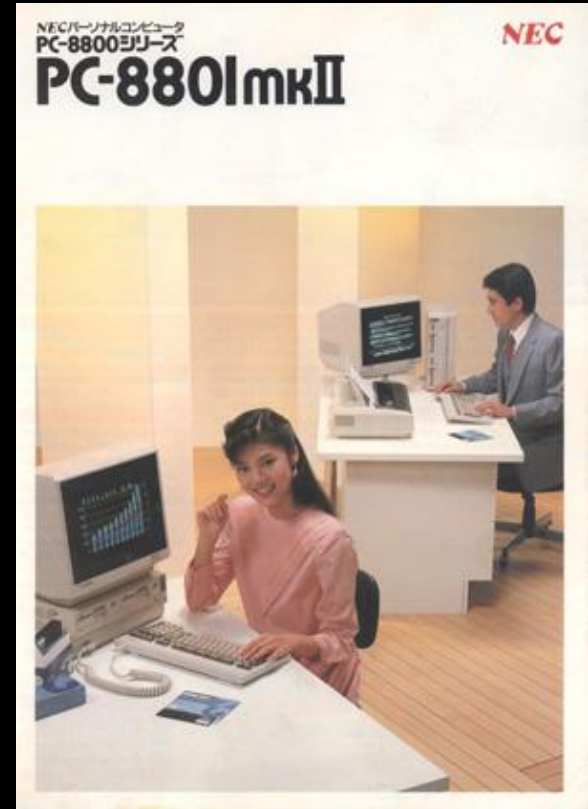
**defend.snd**



# 1985: FM In Your Home (in Japan)

1985 NEC PC-8801mkII

- YM2203 (also Yamaha chip)



# 1988: SEGA has FM, Nintendon't

## SEGA MegaDrive/Genesis

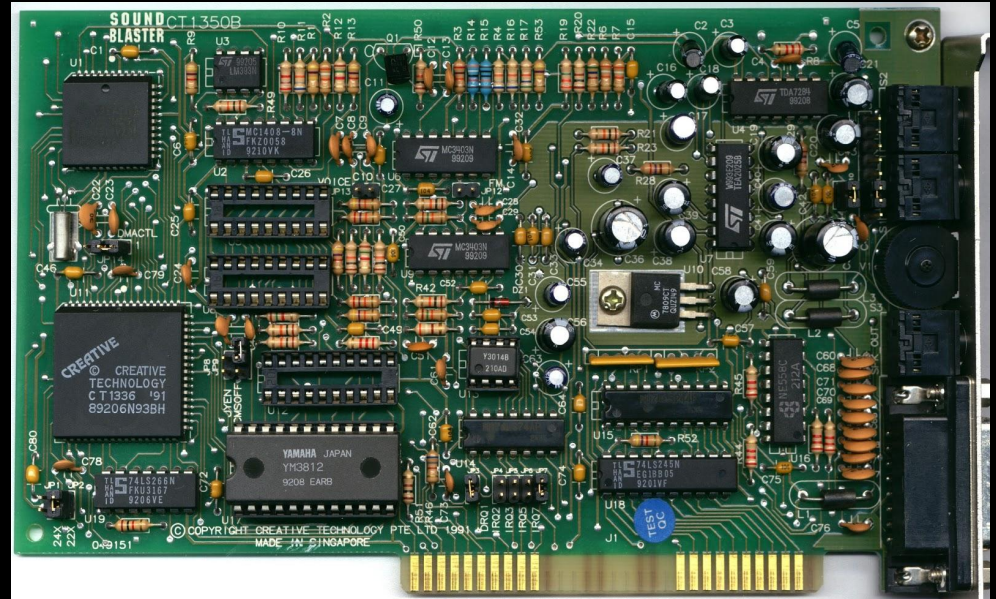
- YM2612 (yet another Yamaha chip)
- 1 channel can play 8-bit samples



# 1989: FM In Your PC

## The Sound Blaster

- YM3812 (Yep, still Yamaha)



# SNATCHER

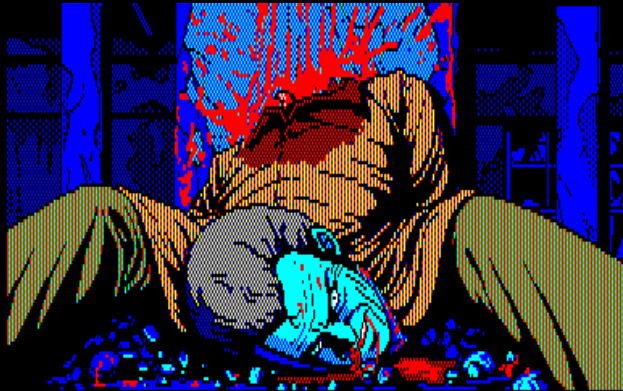
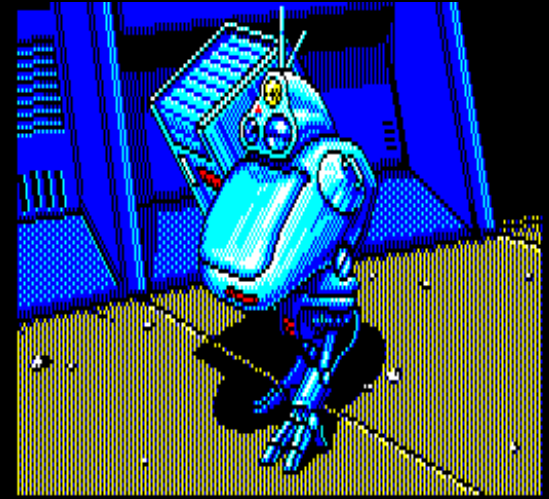
Metal Gear Mk. II

Director: Hideo Kojima

Cyberpunk adventure, 1988 Konami

Japan: PC-88, MSX2, PSX, PCE, SAT

West: Only Mega-CD



# Marble Madness Development

Design Time vs. Game Time:

Can be completed in 3 minutes (if you're really, really good)

