Real Sound for 8-bit Apple II's

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The Apple II speaker

(and cassette output)

- Can only toggle “1-bit output”
- Can’t choose “polarity”
- Doesn’t respond to alternate low-frequency toggles

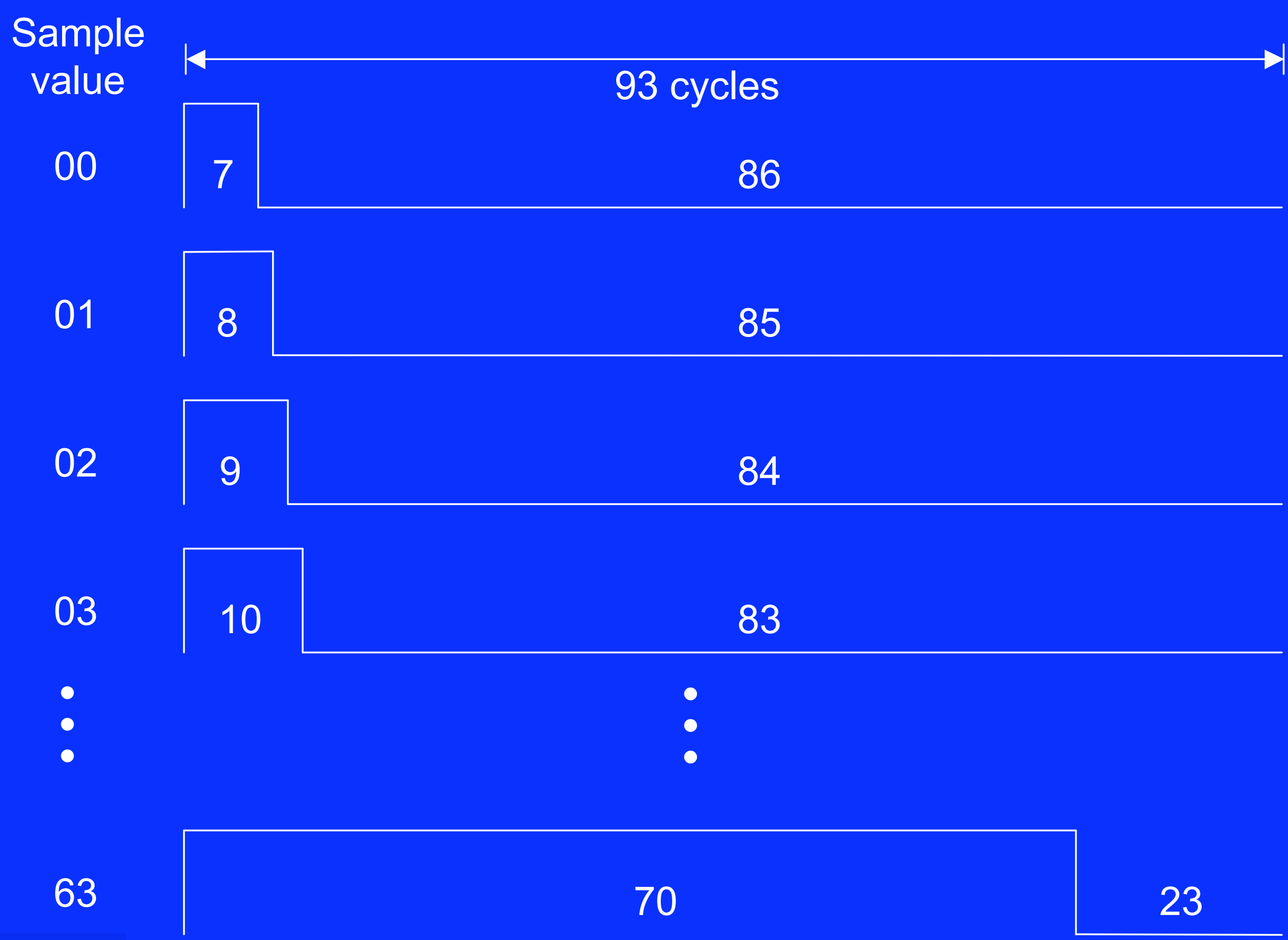
Simple Sound

- Double-frequency timing loop
  - Squarewaves (beep, etc.)
- Actual frequency timing loop
  - Non-50% duty cycle, timbre (Red Book)
- Infinitely-clipped 1-bit sound
  - Distorted speech and music (Hex Dump Reader, Audex, etc.)

Complex Sound

- Ultrasonic timing loop with variable duty cycle pulses
  - Electric Duet (4 duty cycles = 2-bit precision)
  - Software Automatic Mouth (?)
  - Sampled sound (many duty cycles)

Variable Duty Cycle



Software DACs

- Sample rate (11.025kHz)
- Pulse rate (11.025kHz / 22.05kHz)
- Bits of precision (3, 4, 5, 6)

Timing Constraints

- 11kHz = 93 Apple II cycles/sample
  - 1/93cy = 10.973kHz, -52Hz, -0.005%
  - 1/92cy = 11.092kHz, +67Hz, +0.006%
- Apple II timing resolution = 1 cycle
- 4 cycles required to flip speaker
  - 8 cycles per pulse, 4-cycle minimum width
- Sound amplitude = Δwidth / period

Software DAC loop example

first try: constant 93 cycles, 6-bit precision

loop:

4 **[Start pulse]**
3 JMP vector1
<0-63 Variable delay>
4 **[End 7-70 cycle pulse]**
3 JMP vector2
<63-0 Complementary variable delay>
5 Fetch next sample
2 Check for end (if =0)
10 Increment ptr,Y
6 Shift sample
4 Get vector1
4 Set vector1
2 Transform vector1--> vector2
4 Set vector2
3 JMP loop

117 cycles **** 24 cycles too long! ****

DAC611

Constant 93 cycles, 93-cycle pulse period, 6-bit precision

loop:

4 **[Start pulse]**
6 Get vector1
4 Set vector1
3 JMP vector1 (-->long: if >$7F)
<2-33 delay>
4 **[End 19-50 cycle pulse]**
4 Transform vector1-->vector2
4 Set vector2
3 JMP vector2
<33-2 complementary delay>
10 Increment ptr,y
5 Fetch next sample
2 Test for end if =0
6 Shift 3
3 JMP loop
93 cycles

long:

17 (entered at +17 cycles)
<2-33 delay>
11 Increment ptr,y
4 Transform vector1-->vector2
4 Set vector2
5 Fetch next sample
2 Test for end if =0
6 Shift 3
4 **[End 51-82 cycle pulse]**
3 JMP vector2
<33-2 complementary delay>
2 NOP
0 [falls into loop]
93 cycles

[Greg Templeman, 1993]

Pulse frequency of 11kHz is intolerable to many listeners.

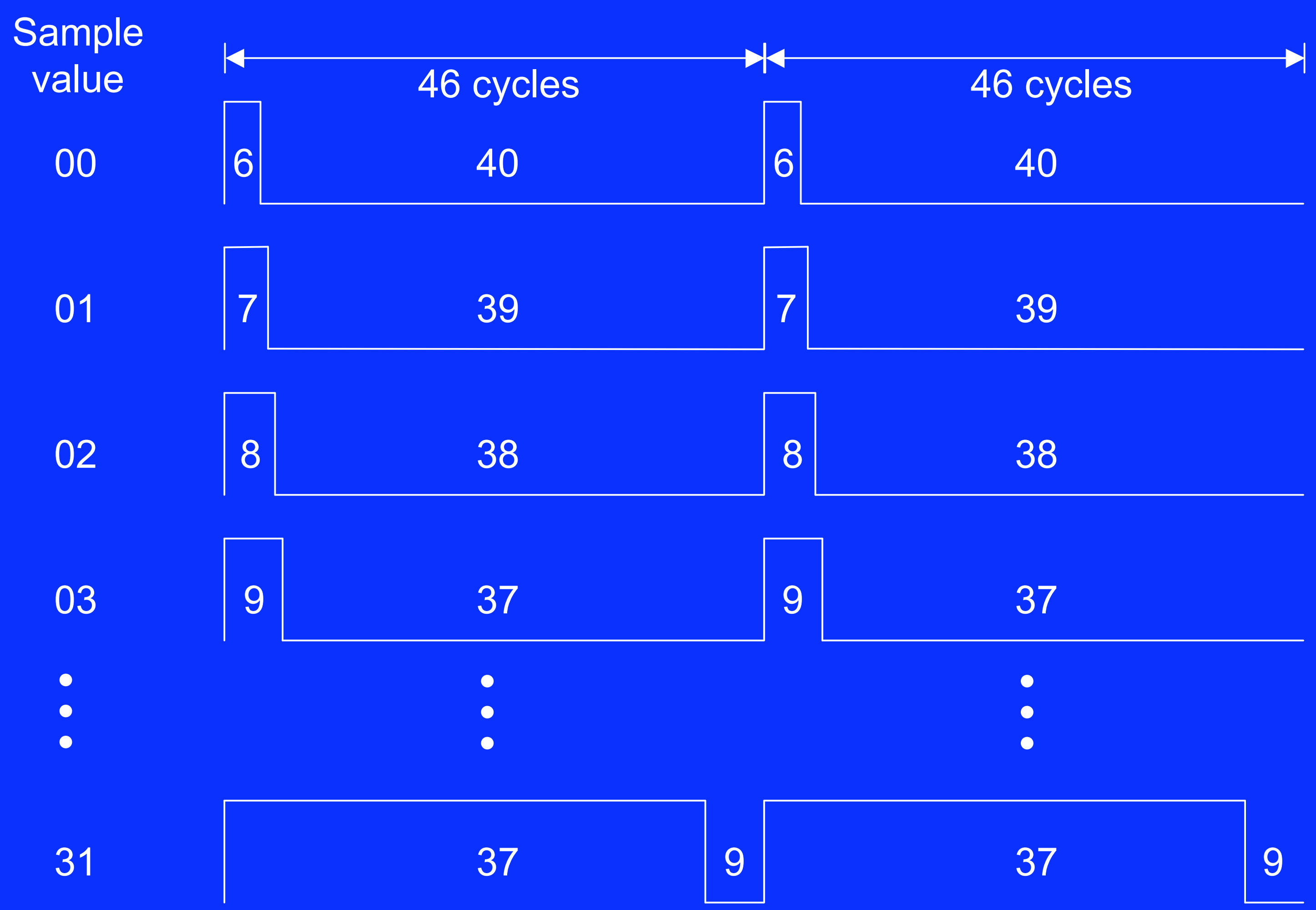
DAC522

Constant 92 cycles, 46-cycle pulse period, 5-bit precision

- Logically 32 separate pulse generators
  - Each generates two pulses in 92 cycles
  - Each fetches next sample and sets vector
  - Then it vectors to next generator
  - Computation is **distributed** between pulse edges

Pulse frequency of 22kHz is inaudible!

DAC522 Pulse Generators



Other Problems

- Starting and stopping without “pops”
  - Solution: Don’t stop!
    - “Ramp” waves to start and stop at 0 level
    - generate continuous 0-level pulses (except for key clicks)
- Generating long sounds at 11kB/second
  - Solution: Direct Digital Synthesis
    - Resample wavetables on-the-fly
    - Use envelope table for dynamics

RT.SYNTH

Single-voice multi-timbral real-time wavetable synthesizer

- Voice waves are resampled on-the-fly to note frequencies
  - Frequency = Integer.fraction sample index increment
- Can support as many different voices as fit in memory
  - A voice is represented as a set of single-cycle **waveshapes** selected by a table representing the **envelope** of the voice.
  - This supports
    - Tonal voices with complex attacks that are resampled
    - Atonal sounds that are played as “waves”
- Wavetable waveforms are stored starting and ending at zero amplitude to minimize pops
- “Resting” or idling sound is the zero-level pulse train

DAC522 Generator Code

```
0800: 8D 30 C0 >6    gen0     sta   spkr        ; <==== start time: 0
0803: EA       >7             nop               ; Kill 2 cycles
0804: 8D 30 C0 >8             sta   spkr        ; <===== stop time: 6
0807: 85 EB    >9             sta   ztrash      ; Kill 3 cycles
0809: E6 ED    >10            inc   scount      ; Compute envelope
               >11            ciny
080B: F0 01    >11            beq   *+3         ; If =, branch to iny
080D: A5       >11            dfb   $A5         ; "lda $C8" to skip iny
080E: C8       >11            iny
               >11            eom
080F: 18       >12            clc
0810: A5 EC    >13            lda   frac        ; Compute next sample
0812: 65 FE    >14            adc   freq
0814: 85 EC    >15            sta   frac
0816: 8A       >16            txa
0817: 65 FF    >17            adc   freq+1
0819: AA       >18            tax
081A: B1 06    >19            lda   (env),y     ; Next sample page
081C: 8D 30 C0 >20            sta   spkr        ; <==== start time: 46
081F: EA       >21            nop               ; Kill 2 cycles
0820: 8D 30 C0 >22            sta   spkr        ; <===== stop time: 52
0823: 85 EB    >23            sta   ztrash      ; Kill 3 cycles
0825: 8D 2A 08 >24            sta   :ptr+2
0828: BD 00 00 >25   :ptr     ldaa  0*0,x       ; Fetch sample.
082B: 8D 3C 08 >26            sta   :sw0+2
082E: C6 FC    >27            dec   dur         ; Decrement duration
               >28            cdec  dur+1
0830: F0 02    >28            beq   *+4         ; If eq, branch to dec
0832: EA       >28            nop               ; Else kill 2 cycles and
0833: AD       >28            dfb   $AD         ;  "lda xxxx" to skip dec
0834: C6 FD    >28            dec   dur+1       ;    of zero-page param.
               >28            eom
0836: A5 FD    >29            lda   dur+1
0838: F0 03    >30            beq   :quit       ; Finished.
083A: 4C 00 00 >31   :sw0     jmp   0*0         ; Switch to gen, T = 89
               >32
083D: 4C 40 09 >33   :quit    jmp   quit
```

CRATE.SYNTH

8-voice multi-timbral MIDI playback wavetable synthesizer

- Uses AppleCrate machines as eight digital oscillators
- MIDI.COMPILER
  - Merges multi-stream MIDI events
  - Tempo changes complicate timekeeping
  - Schedules 8 digital oscillators in one pass
  - Tries to re-use oscillators with a voice history
  - When >8 oscillators needed, “steals” from oldest note
- CRATE.SYNTH
  - Uses NadaNet to load the 8 oscillator machines
  - Starts them all in sync (AppleCrate drift is ~1 ms. in 40 sec.)

Questions and discussion...