GR8BIT
THE REAL ENGINEERING EXPERIENCE

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Adding a multimedia capability:
a Covox device

Introduction

In standard configuration GR8BIT, as MSX-compatible platform, features AY-3-8910-based programmable sound generator, which, while successfully used by the games and other software, provides limited flexibility in terms of the universal output of the signal waveforms and discretization of the output volume.

With PSG every channel can have exponential discretization of the volume, from 0 to 15, and a set of pre-defined waveforms. There were projects which aimed to use three PSG channels in combination to create PSG output sequences emulating sound as close to the desired waveform as possible, but it is a workaround rather than solution. One of the notable projects is *PCM encoder* by Daniel Vik, Vincent van Dam and Arturo Ragozini; you first convert sound file to the PSG-digestible command sequences using sophisticated algorithm, and then feed these command sequences to the PSG device.

Covox device (named by the name of the company selling the device back in 80s) is the simple DAC (digital-to-analog converter) based on the passive resistive elements using *resistor ladder* schematic. Covox device connects to the machine's parallel port, which supplies digital representation related to the level the voltage required at the Covox device output.

Does MSX have *resistor ladder* designs in it?

The answer is **yes**. One of the very well-known multimedia devices for MSX which uses resistor ladder is SCC (Konami Sound Custom Chip). Fig. 1 depicts the resistor ladder, and fig. 2 depicts its internal circuit diagram. The least significant bit (bit 0) of the SCC resulting 11-bit digital waveform representation, is connected to the pins 13. The most significant bit (bit 10) is connected to the

pin 3. Pin 2 is an output to the sound mixer, and resistor R1, connected to the ground, serves as a definition of the output impedance of the circuit. Please note that this device, as well as board with SCC chip, does not have decoupling capacitor, as it is expected to be installed at the input of the mixer.

Figure 1. Konami resistor ladder soldered into the SCC-based cartridge
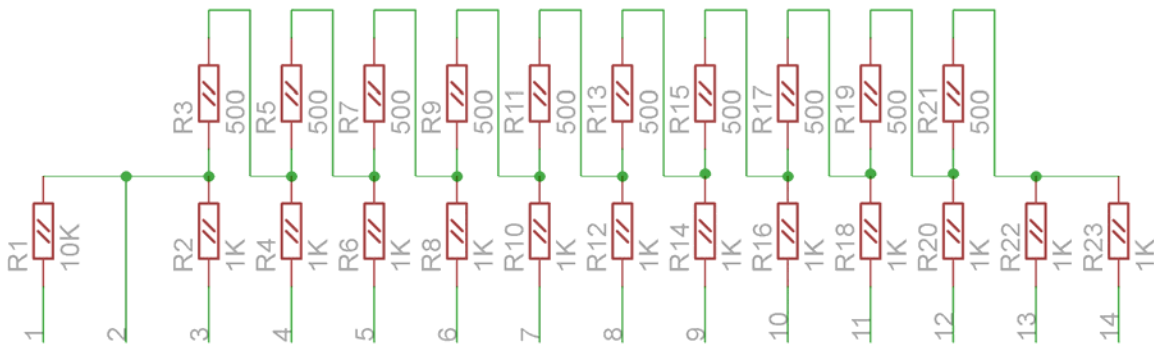

Figure 2. *Konami 051650* resistor ladder internal circuit diagram

How our Covox device will look like

Design of the Covox circuit is more or less unified, with minor differences in the value of resistors, existence of filtering and decoupling capacitors, and output impedance resistor. Look at the circuit shown on the fig. 3. As you may have read in the Wikipedia article about resistor ladders (recommended reading!), it is very important to have one set of resistors to be twice of value to another set. On this diagram, we have 7.5K and 15K resistors, which define the current, and thus amplitude of the voltage at the positive input of the capacitor C1.

In simple words, high level at the output D0 will add specific level of the current (and thus voltage) to the cumulative output waveform, and influence of D0 will be twice less than D1, influence of D1 will be twice less than D2 and so on. D7 will have maximal influence on the level of voltage of the output signal. Keeping ratio between sets of resistors will ensure that these influences are added in *linear* way, so that, for example, there will be same voltage level delta between having 03h at the data bus (D0 and D1 are high level, others are low), and 04h (D4 is high level, others are low) as in the all other combinations.

Also very important to note that *center* of the digital waveform element (the number represented by the bit set of D7...D0), or the zero reference point for the whole waveform, should be a value of 080h (bit D7 is high, others low). Therefore positive level of voltage will be represented with numbers 081h and above (up to 0ffh), and negative level of voltage will be represented by numbers 07fh and below (down to 00h). Trying to play 00h-centered waveform will result in corrupt sound. Conversion from 00h-centered to 080h-centered waveform (also called as *sample*) is performed by signed addition of 080h to the former.

In order to increase the *volume* of the signal which passes from C1's negative pin to the mixer, you may decrease values of the resistors, still keeping the ratio in their values. However you should be aware that below some minimal value of the 2R resistors, current from high level D outputs will start flowing to the D outputs which are in the low level, and resulting voltage level at the C1 (and thus sound you hear) will become corrupt. This minimal value is dependent on the level of current chip behind D7...D0 lines is able to supply at high level and absorb at low level.
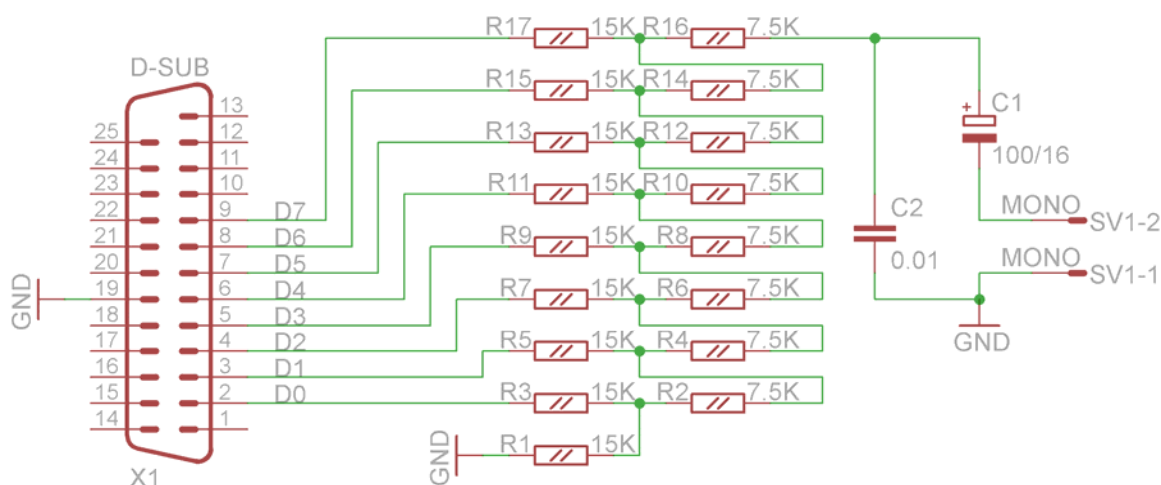

Figure 3. Typical circuit diagram of the Covox device

How Covox device works in detail: 2-bit Covox DAC

Let's consider simpler version of the device, 2-bit Covox (fig. 4). In this configuration we have four combinations of the input signals [$x_1 x_0$]: 00, 01, 10 and 11. Figure 5 shows transformed schematic diagrams for every case, with ground at the bottom and supply at the top. We will make several specific assumptions when looking into the details:
- Current does not flow through output line;
- Input lines are assumed to be logical 1 (connected to supply) of logical 0 (connected to ground).

Both assumptions represent ideal operation of the circuit. In real life circuit design, as well as properties of input and output devices will add distortions to its operation:

- Device connected to the output of the circuit will drain (or add) current flow to the circuit, distorting ideal output values. That's why Covox device, by default, has current limiting resistor at its output (R_{16} on fig. 3), increasing impedance of the output to at least value of R, and a capacitor (C1 on fig. 3) achieving DC-DC decoupling of the Covox and further circuit;

- Input lines' voltage levels may be lower than supply (U) for logical 1, and higher than 0 for logical 0, adding/draining the different current than calculated.
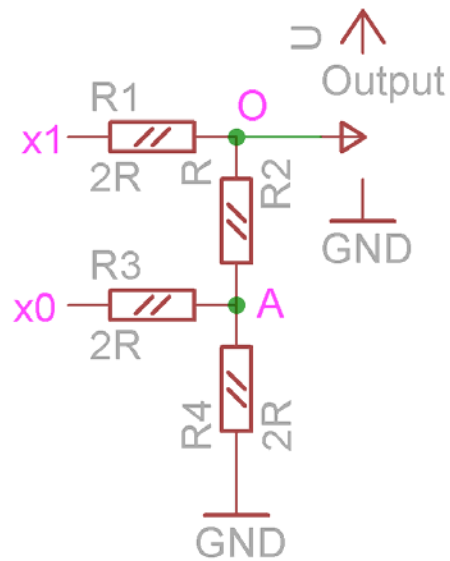
Figure 4. Two-bit Covox device

Please note that all voltages are measured against ground (GND) if not specified otherwise.

Combination 00: $x_1=0$, $x_0=0$ (fig. 5a). In this case supply voltage does not play any role, and current does not flow anywhere. Output receives ground, or voltage level 0.

Combination 01: $x_1=0$, $x_0=1$ (fig. 5b). First, we will calculate cumulative current I, flowing through circuit. Cumulative passive resistance of the circuit equals to

$$R_c = R_3 + \frac{(R_1 + R_2) * R_4}{(R_1 + R_2) + R_4} = 2R + \frac{3R * 2R}{5R} = \frac{16}{5}R .$$

Thus current flowing will be $I = \dfrac{U}{\frac{16}{5}R} = \dfrac{5U}{16R}$. Now we find out the value of

voltage between ground and point A:

$$U_A = U - 2R * \frac{5U}{16R} = U - \frac{5}{8}U = \frac{3}{8}U .$$

Now basing on the value of U_A, we calculate the value of current flowing through R_1 and R_2 part of circuit:

$I_{R1R2} = \dfrac{\frac{3}{8}U}{3R} = \dfrac{U}{8R}$, and the voltage on the R$_1$ will be $U_o = \dfrac{U}{8R} * 2R = \dfrac{1}{4}U$. In other words, with the input signal combination 01 we have one fourth of the supply voltage on the circuit output.

Combination 10: $x_1=1$, $x_0=0$ (fig. 5c). Cumulative passive resistance of the circuit between ground and supply equals to $R_c = 2R + R + R = 4R$, and current flowing through it $I = \dfrac{U}{4R}$. Voltage on the output will be equal to $U_o = \dfrac{U}{4R} * 2R = \dfrac{1}{2}U$. In other words, with the input signal combination 10 we have half of the supply voltage on the circuit output.

Combination 11: $x_1=1$, $x_0=1$ (fig. 5d). Schematic looks absolutely the same as in combination 01, but connected reversely to the supply and ground. Cumulative current is $I = \dfrac{5U}{16R}$; voltage in point A is $U_A = \dfrac{5}{8}U$, voltage between supply and point A is $U_{UA} = U - \dfrac{5}{8}U = \dfrac{3}{8}U$; current flowing is $I_{R1R2} = \dfrac{\frac{3}{8}U}{3R} = \dfrac{U}{8R}$, and voltage between supply and output is $U_{UO} = \dfrac{1}{4}U$, thus between ground and supply $U_O = U - \dfrac{1}{4}U = \dfrac{3}{4}U$. In other words, with the input signal combination 11 we have three halves of the supply voltage on the circuit output.

Now let's visualize values with the table:

| Combination	Cumulative circuit current	Output voltage
00	0	0
01	5U/16R	U/4
10	U/4R	U/2
11	5U/16R	3U/4

What we learn from the mathematical exercise above we made for 2-bit Covox DAC? Here're the points:

- With Covox-type DAC, you will never attain supply voltage on its output. Maximal value of the voltage in ideal conditions is $\dfrac{n^2-1}{n^2}U$, where n is a number of circuit inputs;
- Output voltages ideally divide scale of supply voltage onto the number of combinations, receiving the voltage of the lowest boundary of the range;

 Status: **Released**

- Value of resistor R defines the current flowing through the circuit during its operation, with maximal current observed on the combination 01 equal to $\dfrac{5U}{16R}$ (for 2-input DAC). Decreasing the value of R increases load onto the supply source (and inputs), but at the same time decreases distortions by the currents flowing to/from inputs and output;
- DAC circuit *will* draw current from its inputs. Devices providing input voltages $[x_0, x_1, \ldots, x_n]$ to the circuit should have enough power to keep voltage levels under the circuit's load.
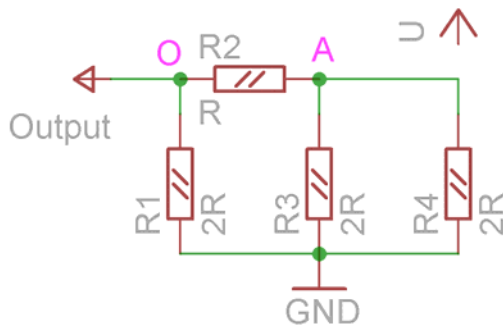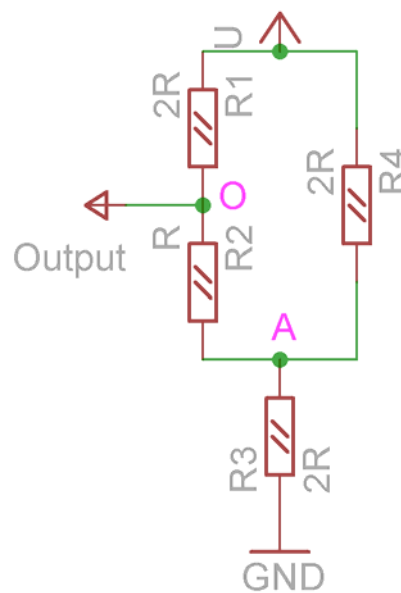

(a) combination 00
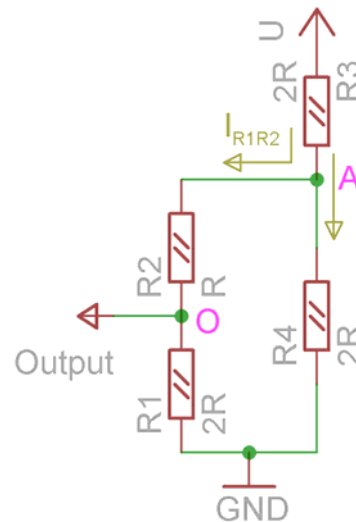
(b) combination 01
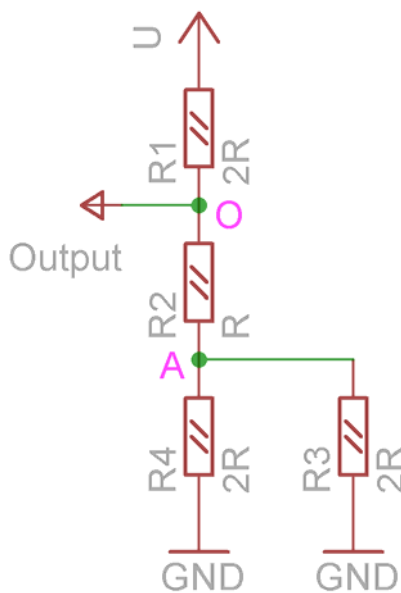
(c) combination 10   (d) combination 11

Figure 5. Transformed circuit diagrams for all four combinations of input lines

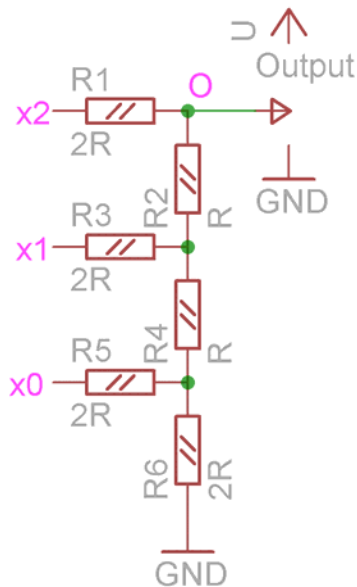**More complex example: 3-bit Covox DAC, combination 101**

Figure 6. Three-bit Covox device

In previous chapter we considered relatively simple design, but will our findings hold the true for more complex one? Let's see on the example of the 3-bit DAC, and on the specific combination. Calculations involve more steps as there're more elements involved, and features one very interesting transformation, called *Δ-Y transformation* (see the link to theory at the end of the article).

Three-bit DAC (fig. 6) has three digital inputs, and 8 possible input binary states (000b to 111b). We need to identify, which voltage, under the same assumptions as in previous chapter, we will have in the point O when we apply $x_2=1$, $x_1=0$, $x_0=1$ input binary state.

Redrawn diagram under this 101 condition is shown on fig. 7a. You can recognize the device from the fig. 6. However fig. 7b shows the same as 7a, it consolidates same signals applied to the circuit – power and ground wires. In order to identify the voltage in the point O, we need to identify current flowing through resistor R1, but to know it we will have to analyze almost all the circuits flowing between power wires.

Fig. 7c consolidates R_1 and R_2 into R_{12} with value 3R. It is clear, that we now have bridge resistor network, and to proceed we will apply Δ-Y transformation to the resistor triangle $R_3/R_4/R_6$. After transformation, we get equivalent diagram shown on fig. 7d, with resistors of the following values:

$$R_{34} = \frac{R_3 \cdot R_4}{R_3 + R_4 + R_6} = \frac{2R \cdot R}{2R + R + 2R} = \frac{2R^2}{5R} = \frac{2}{5}R \; ; \qquad R_{64} = \frac{R_6 \cdot R_4}{R_3 + R_4 + R_6} = \frac{2}{5}R \; ;$$

$$R_{36} = \frac{R_3 \cdot R_6}{R_3 + R_4 + R_6} = \frac{2R \cdot 2R}{2R + R + 2R} = \frac{4}{5}R \; .$$

Now we consolidate serial resistors from the left and right arms of the schematic, getting resistors R_{3412} and R_{645} (fig. 7e):

$$R_{3412} = 3R + \frac{2}{5}R = \frac{15}{5}R + \frac{2}{5}R = \frac{17}{5}R \; ; \; R_{645} = 2R + \frac{2}{5}R = \frac{12}{5}R \; .$$

After that we consolidate parallel resistors, and getting fig. 7f:

$$R_{3412645} = \frac{R_{3412} \cdot R_{645}}{R_{3412} + R_{645}} = \frac{\frac{17}{5}R \cdot \frac{12}{5}R}{\frac{17}{5}R + \frac{12}{5}R} = \frac{\frac{204}{25}R^2}{\frac{29}{5}R} = \frac{204R^2}{25} \cdot \frac{5}{29R} = \frac{204}{145}R.$$

Now again consolidating serial resistors R_{36} and $R_{3412645}$, and get single resistance between supply wires (fig. 7g):

$$R_{363412645} = \frac{204}{145}R + \frac{4}{5}R = \frac{204}{145}R + \frac{116}{145}R = \frac{320}{145}R = \frac{64}{29}R.$$

Therefore, total current flowing through the original circuit will be equal to

$$I = \frac{U}{\frac{64}{29}R} = \frac{29U}{64R}.$$

So we go back, to original diagram, step by step. Voltage at the R_{36} equals to $U_{36} = \frac{29U}{64R} \cdot \frac{4}{5}R = \frac{29}{80}U$, and voltage on $R_{3412645}$ will be $U_{3412645} = U - \frac{29}{80}U = \frac{51}{80}U$ (fig. 7f, the value we need). This means that resistor R_{3412} (fig. 7e) is passing current equal to $I_{3412} = \frac{\frac{51}{80}U}{\frac{17}{5}R} = \frac{51U}{80} \cdot \frac{5}{17R} = \frac{3}{16}U.$

The same current is flowing through R_{34} and R_{12} (fig. 7d and 7c), and R_1 and R_2 (fig. 7b). Therefore voltage on the resistor R_1 equals to $U_1 = \frac{3}{16}U \cdot 2R = \frac{3}{8}R$, and voltage between output and ground will be $U_O = U - U_1 = \frac{5}{8}U$.

So what we learnt from this exercise? It confirmed our findings with 3-bit DAC that voltage scale is divided into n^2 ranges (1/8), and voltage value is at lower boundary of the range for every combination: 101 binary is 5 decimal, resulting 5U/8 potential of output relative to ground.
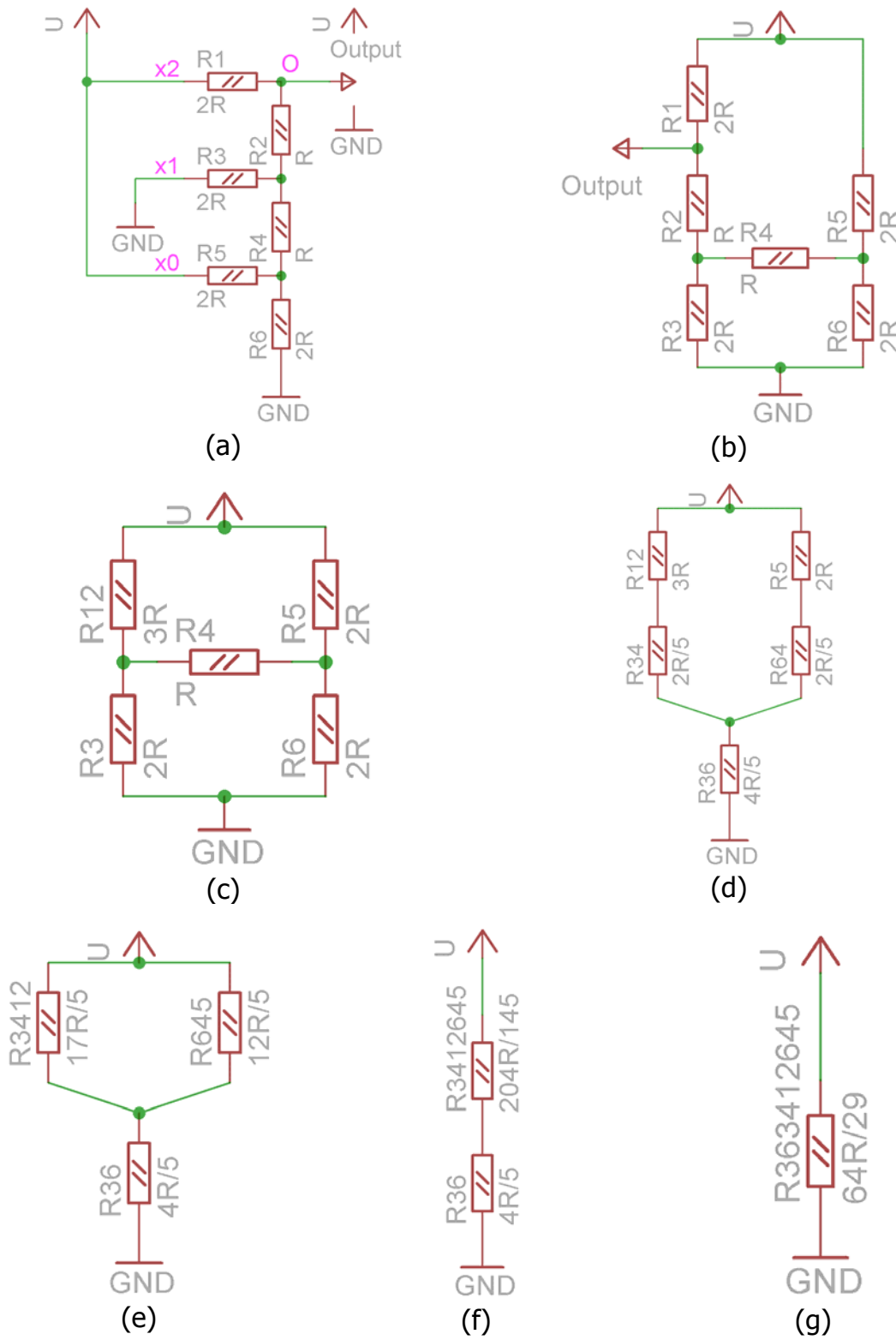
(a)

(b)

(c)

(d)

(e)

(f)

(g)

Figure 7. Analysis of 3-bit Covox DAC, combination 101

Building our Covox device

We decided to take 2R value of 6.2kOhm, and thus having R value to equal to 3.1kOhm. To get best quality possible we chosen 1% tolerance resistors, and as 3.1kOhm resistors are not easily available on the market, construct this value by connection two 6.2kOhm resistors in parallel. In general case, when you connect two, three or more resistors in parallel, resulting resistance is calculated by the following formula:

$$R = \frac{R_1 * R_2 * \ldots * R_n}{R_1 + R_2 + \ldots + R_n},$$

and in our particular case with two resistors of same value it will be

$$R = \frac{6.2 * 6.2}{6.2 + 6.2} = \frac{38.44}{12.4} = 3.1 (\text{kOhm}).$$

Therefore we will need 9+8*2=25 resistors of the same 6.2kOhm nominal.

In addition to resistor, we will need one ceramic filtering capacitor (0.01µF), one electrolytic capacitor (100µF/16 volts), and 25-pin two row *male* D-SUB connector with casing as large a s possible to hold the electronics we are to build into it. We will also need a piece of shielded wire, and connector at another end of this wire (fig. 8).
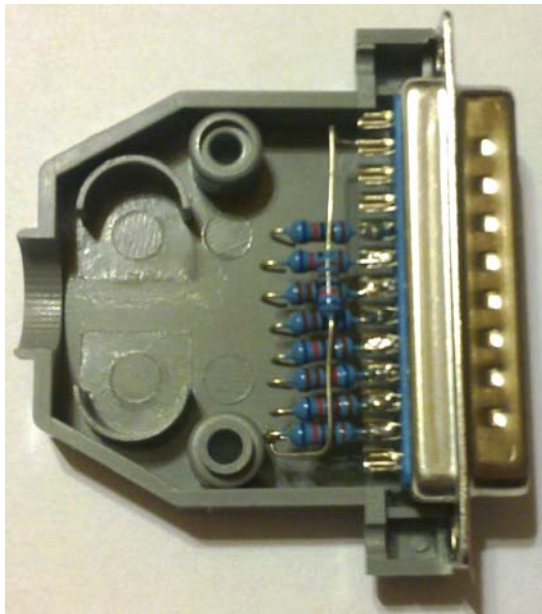

Figure 8. Set of parts to build a Covox device
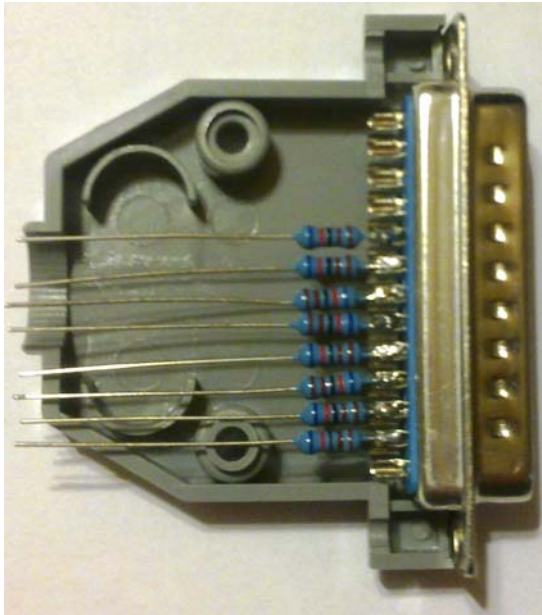
(a) Cut one side of the pins of 8 resistors, leaving about 5 mm to solder to the connector's pins
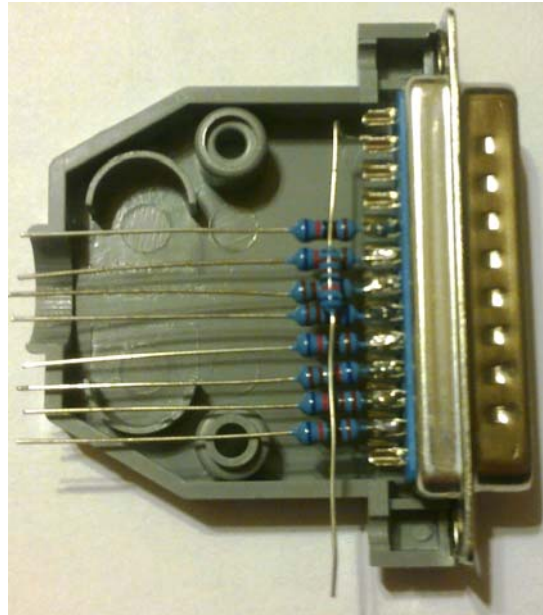
(b) bend R1's pin and solder it to the ground pin of connector (in our case, to pin 25)

(c) cut 8 resistors' other pins, and bend small hooks at their ends carefully. Solder R_1 to the R_3
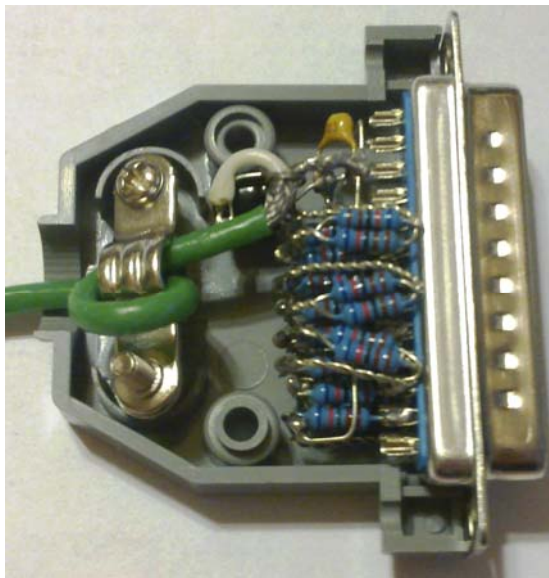

(d) connect 8 pairs of the resistors to form a circuit of twice less nominal

Figure 9. Assembling the device

(e) Bend their pins as shown above, and start soldering to the hooks of the resistors, alternating the sides (i.e. R_3/R_5 from one side of the connector, R_5/R_7 from another side)

(f) at the end solder C_1, C_2, solder shielded wire (which was previously prepared as described in your GR8BOOK part II subchapter 3.4)

(g) put electric tape so that resistors at the connector sides do not short-circuit with its body, and wire's shield do not short-circuit with any junction

Figure 9. Assembling the device (continued)

You have several options how to connect components to each other – use breadboard, or use point-to-point connection. Given the number of components, their size and relatively small size of the connector casing, we have chosen to use point-to-point connection. In this style of build, the most important task, along to ensuring that all components are connected reliably, we should ensure

that, as they are only fixed with their pins, they do not short-circuit with other components. Covox does not have components which excessively heat, and we just use electrical tape to isolate component pins and junctions.

Here's the list of steps we have taken:
- Connect resistors to the D7…D0 lines (fig. 9a);
- Connect R1 to the ground (fig. 9b);
- Bend hooks of the D7…D0 resistors, and connect R_1 to R_3 (fig. 9c);
- Join resistors in pairs to create assemblies of nominal R (fig. 9d);
- Bend pins of these pairs, and solder then to the hooks of the D7…D0 resistors, alternating the D-DUB connector sides (fig. 9e). At every pair soldered, ensure that assembly fits into the connector body, and if not, bend resistors or re-solder them;
- Solder C_1, C_2, attach shielded cable, put into the casing to ensure assembly fits (fig. 9f);
- Put electric table ensuring that no air-hanging pins short circuit with each other or with connector's body, as well as with shielded wire shield (fig. 9g);
- Close the casing of the connector, and test it!

Testing the Covox device within your GR8BIT

Well, you can test it in your PC's parallel port too, but let's focus on which tools are available to test in on GR8BIT.

We provide program called COVOX which streams media file in the format of 11025Hz, 8 bit sample and single channel, to the parallel port of your GR8BIT. It also visualizes the waveform on the screen. This program runs properly on the accelerated GR8BIT because it heavily uses I/O access (to printer port 091h and video ports 099h and 098h), and GR8BIT is steadily running at the CLKLO speed (please refer to *KB0009: Accelerating your GR8BIT*).

The command line format is

COVOX [filename]

where "filename" is a name of the media file in WAV format, in 8.3 notation. This file can be of any size.

Program identifies the size of the RAM available, and uses all its pages from #4 up pre-fetching the data to play. As buffer had been played, playback stops until new chunk of the wave data is loaded into the RAM. Due to the speed constraints it is not possible to perform playback and mass storage I/O (waveform data read) simultaneously. COVOX.COM works in DOS1 mode only, because it bypasses DOS2 memory allocation routines. It is rather than demonstration and a piece for your further development, than fully functional application. It can be downloaded in the **Downloads** section of the website.

COVOX.COM works fine in the emulators, if you insert "SiMPL/Covox DAC" into parallel port in BlueMSX, "simpl" device into the printer port in OpenMSX (fig. 10).

(a) GR8BIT
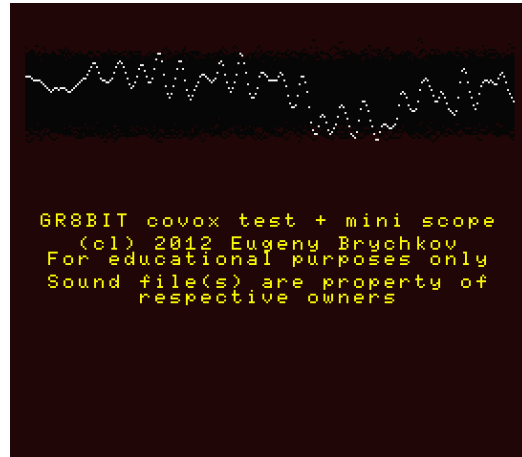
(b) BlueMSX

Figure 10. Running COVOX.COM in the real machine (a) and emulator (b)

Sources and information for further reading:

- Wikipedia (2013) Δ-Y transformation, available online at http://en.wikipedia.org/wiki/Y-%CE%94_transform (accessed on 23-Oct-2013)
- Wikipedia (2012) *Covox Speech Thing*, available online at http://en.wikipedia.org/wiki/Covox (accessed on 19-Oct-2012)
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- Vik, D., van Dam, V., Ragozini, A. (2006) *PCM Encoder*, available online at http://vik.cc/dvik-joyrex/tools.html (accessed on 19-Oct-2012)
- Wikipedia (2012) *Electrical Impedance*, available online at http://en.wikipedia.org/wiki/Electrical_impedance (accessed on 19-Oct-2012)
- Wikipedia (2012) *Point-to-point construction*, available online at http://en.wikipedia.org/wiki/Point-to-point_construction (accessed on 19-Oct-2012)

End of KB0010 "Adding a multimedia capability: a Covox device".

KB article release notes: KB0010 was initially released on October 19, 2012. It was amended:
- October 09, 2013 by separating and enhancing chapter on how Covox operates;
- October 23, 2013 by adding section about 3-bit DAC and Δ-Y transformation.