

# Viability of Repairing a PolyMoog Keyboard: a case study

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## Abstract

*This paper examines the viability of repair of a vintage synthesizer, the Moog PolyMoog Keyboard. This instrument provides some classic sounds and when fully functional is pleasing to play. Its main renown, however, is its unreliability. For this model of synthesizer repair cannot be assumed. These instruments were made in small numbers and few now exist that are in complete working order. The project involved the successful repair of a defunct PolyMoog Keyboard with multiple faults, and concludes that, with some provisos, repair is viable. An overview of the PolyMoog design rationale is included.*

## Section 1 Background

My first experience with a PolyMoog was in a local music shop in the late 1970s. I remember being quite taken with the ribbon controller. I don't recall the price, but the exchange rate of the NZ dollar in 1978 was USD \$0.50, so given it sold for \$5000 in the USA it must have been around NZD \$10,000. This was well above my budget.

I purchased a PolyMoog Keyboard in 1998. It was languishing at the rear of a Music Shop that was closing down. How long it had been there I don't know, but it must have been traded or taken in for repair. Upon getting it home I found it didn't function at all, so set about repairing it. Back then, the Internet was still fairly new so I didn't have access to any service information. I did manage to fix the power supply and for a short time get some sound out of it. However, it died again soon after. At this point in time other priorities took over so I was not prompted to tackle it again until 2018. I have found it is actually considerably easier to repair now due to being able to source parts online. Apart from the service information provided by Moog Music, there is still little technical information available.



## From Electronic Monophony to Polyphony<sup>1</sup>

The invention of the thermionic triode valve in the early part of the 20<sup>th</sup> Century paved the way for many new electronic inventions, including the musical synthesizer. Most instruments were focused on the new timbres that could be generated, and expression was also a consideration.

The engineering restraints of producing single notes (or even a single sound) matched well with the norms of many acoustic instruments, where tonal interest and expression are paramount (eg the trumpet or saxophone). Much of early electronics development was dedicated to radio, and heterodyne circuits were typically used to form the basis of synthesizers too. Early examples were the Theremin (1920), where hand gestures control the pitch and volume, and the Trautonium (1929) which used a resistive wire pressed onto a plate to control the note played.

One obvious way of making the instrument more user-friendly was to provide a piano type keyboard for control of the sounds. In the late 1920s the Ondes Martenot was invented. It had a keyboard but also a sliding mechanism to provide portamento.

The Hammond Novachord (1939) had formant filters for modifying the harmonic content of the generated waveform, and envelop shaping to mimic wind and string instruments. It was controlled from a keyboard but neither a piano or organ technique was suitable for playing it. This provided a barrier to potential customers and consequently it failed to last long in the market.

It can be seen then, that from early times the design philosophy of the synthesizer was split between having a revolutionary instrument, or one with new sounds but a familiar interface.

The modern history of the synthesizer begins in the 1960s when two American engineers worked on parallel (but independent) paths to invent the voltage controlled synthesizer. Neither Bob Moog or Don Buchla envisaged a keyboard instrument. The design ideal was to have total signal control, such that *any* sound (known or unknown) could be created. Ultimately, R. A. (Bob) Moog collaborated with Herbert Deutsch who presented the idea of controlling the synthesizer modules from a piano-type keyboard. It was this that led to Wendy Carlos' Switched On Bach (1968) bringing electronic sounds to the mass market, popularising the Moog Synthesizer, and at the same time introducing the idea that a music synthesizer is a keyboard instrument.

The design dualism between creating an experimental instrument or a commercial one continued into the 1970s. By the early 1980s the balance had swung firmly in favour of synthesizers with a keyboard. With the introduction of

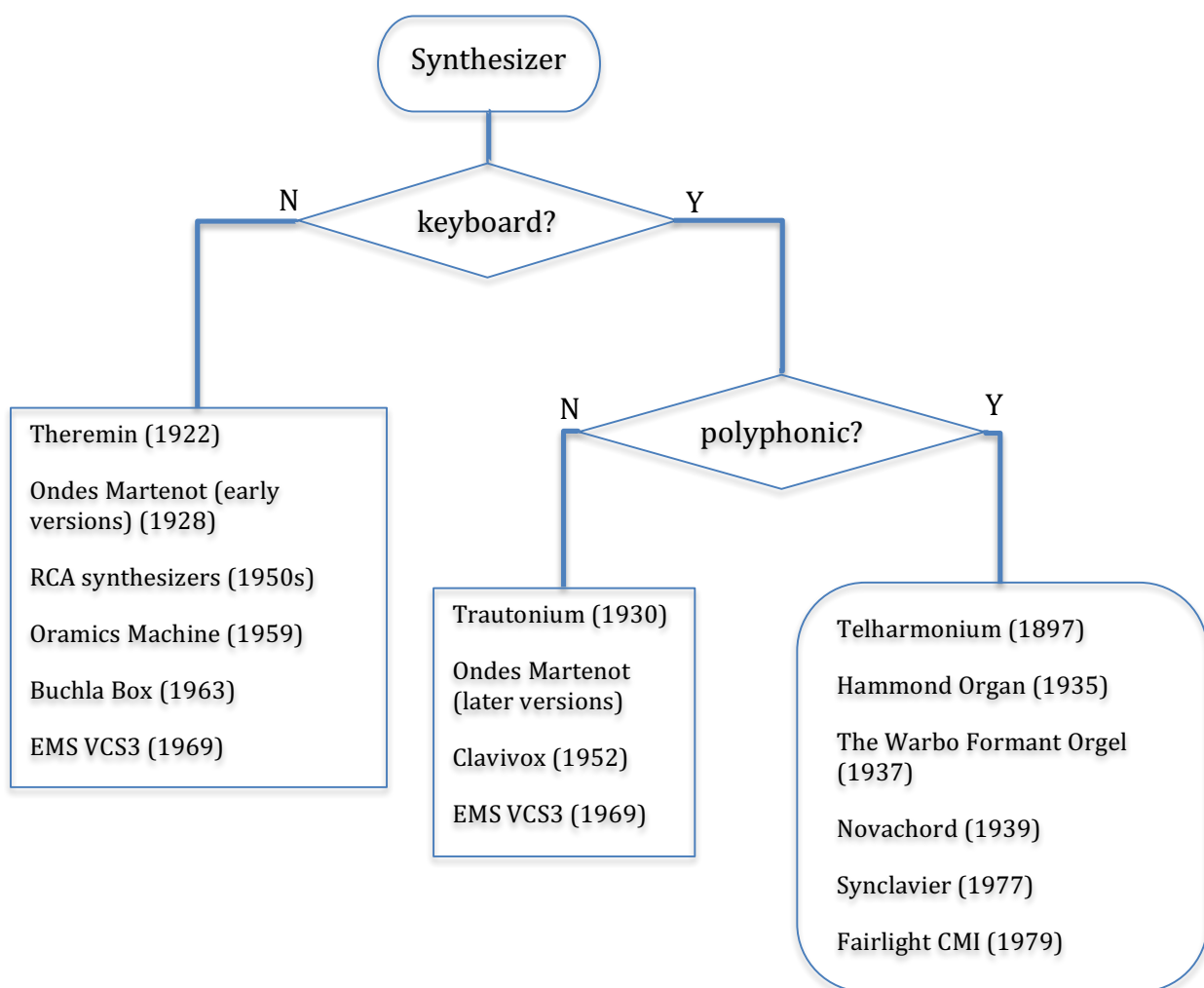
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<sup>1</sup> Since the writing this paper, a series of 12 videos on this subject has been published by Marc Doty:  
[https://www.youtube.com/watch?v=Yty8Rt7bzOk&list=PLHGZsq10nFV\\_hYzC5K0XPVfrLfUYNkBed](https://www.youtube.com/watch?v=Yty8Rt7bzOk&list=PLHGZsq10nFV_hYzC5K0XPVfrLfUYNkBed)



MIDI in 1983 there would be limited further interest in synthesis from an intellectual approach<sup>2</sup>. Indeed, the original ideal of being able to create any sound, imaginable (or otherwise) was lost. This author remembers many conversations of the time, trying to explain the difference between a synthesiser and an electronic organ. Because both had keyboards and were polyphonic it was difficult for the casual observer to notice any distinction.

In the early 1970s commercial synthesizer designers were preoccupied with producing a) a portable preconfigured architecture, and b) reliable oscillator tuning (early synthesizers had obvious problems with this aspect).



*Fig. 1. Categorisation of some notable early electronic musical instruments. Several designs were initially keyboardless, evolving to a keyboard option or with integrated keyboard.*

<sup>2</sup> some universities have continued this approach, while many music departments now use commercial synthesizers.



From this evolution of synthesizer design it is clear to see what the intent of the PolyMoog was. Due to demand from commercial music makers the synthesizer became a *keyboard* instrument, and, by 1975, customers were asking for polyphony. As the keyboard became the accepted way to play a synthesizer it was only natural that players would request more than one note at a time.

Polyphonic electronic instruments were not actually a new idea in the 1970s. Thaddeus Cahill's Teleharmonium of 1906 is an interesting early example. This 200 ton gargantuan was the predecessor to the Hammond organ. Both used electromechanical means (tonewheels) to generate a frequency for each key. The idea of providing a fairly simple tone circuit for each key continued when fully electronic organs were developed<sup>3</sup>.

This way of tone generation design was expensive so manufacturers moved to using a 'divide down' method. Initially twelve separate oscillators, one for each note of the scale, were required. These would generate the frequencies required to suit the top octave of the keyboard. The frequencies were then divided by two to produce the notes one octave lower. This was done as many times as needed to provide tone to all octaves of the keyboard. In the 1970s a more cost-effective method became available due to the availability of Integrated Circuits (ICs). This meant a special IC could be developed to replace the twelve oscillators. This Top Octave Synthesizer (TOS) could generate the 12 semitones in accurate Equal Temperament for the top octave when driven from a high frequency master oscillator.

The human ear is particularly sensitive to relative pitch so the fact that a TOS arrangement would lock all notes in tune would seem to be advantageous. Although it is highly desirable for instruments to stay in tune overall, slight detuning between notes is considered a pleasing effect. All electronic instruments have suffered from the fact that oscillators are essentially bland sounding; acoustic instruments have more richness of sound. To compensate for this deficiency synthesizers must add modulation and time-variant effects. The greater the control of these parameters, the greater the expression of the sounds produced. To return to the TOS: it provided a tidy technical solution, but it also introduced a problem. With no subtle detuning from independent oscillators it produces an uncomplex sound. The typical solution was to provide some form of modulated effect (eg chorusing) on the audio output.

Another important way of providing a suitably complex sound is to vary the oscillators in some way. Techniques available on monophonic synthesis include vibrato, pulse width modulation, and phasing between two (or more) oscillators per voice. This phasing can also be locked or free-running to provide additional variations to the waveform.

The PolyMoog Keyboard<sup>4</sup> is a hybrid musical synthesizer in two senses. It uses digitally controlled analogue circuitry, which was first introduced in Buchla's

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<sup>3</sup> Unusually, the Korg PE-1000 still used this method in the 1970s



System 500 in 1971.<sup>5</sup> Interestingly, that synthesizer had a 61-note keyboard which was highly atypical for a Buchla product. The PolyMoog uses a combination of 7400 series TTL and 4000 series CMOS to control the analogue circuits. By the 1970s, due to these logic ICs being readily available, it became sensible for designers to use them for all the switching functions. This provided more flexibility of design and functionality as well as reduced size, greater reliability and lower cost.

The second hybrid technology used in the PolyMoog is of some interest. A combination of Master Oscillator (MO) / TOS is used with individual voice control for each note. The raw sound source is generated by frequency division from the MO. Voice circuits (one per key) modify the tone and dynamics of this waveform, according to signals from the keyboard. The output of the voice circuits is then fed to a global filter circuit. This resulted in a fully polyphonic instrument (71 notes) with synthesis capabilities.

This was a very ambitious undertaking for Moog and three years elapsed before the first model reached the market. The R & D phase was problematic due to the complexity of design.

ARP were hot on the heels of Moog in the 1970's synthesizer market. Building on the success of the 2600 and Odyssey mono-synths, the company also built a fully polyphonic synthesizer. The Omni was developed as a direct rival product to the PolyMoog so it is of interest to compare the two.

The Omni (and Omni II<sup>6</sup>) was the best-selling synthesizer for ARP, and was perhaps most notably used by The Cars<sup>7</sup> where the string-synth sound can be clearly heard. Analog synthesizer sounds were often rated on ensemble sounds (especially synth-brass), and the quality or 'fatness' is essentially governed by how many oscillators can be assigned to each voice.

The Omni uses a single Colpitts oscillator for its MO. The circuit can be seen in fig. 2. In the 1960s, ARP Industries founder (Alan R. Pearlman) invented several methods for compensating for transistor thermal variations [1], but these patents were assigned to Nexus Industries before ARP was established. This could possibly explain why there is no control loop or thermal stability circuitry in the oscillator design.

To create some movement in the waveform three parallel BBD circuits are employed before the synthesizer's audio output to give a chorus effect. The simplicity of design compared to the PolyMoog still gives good results, with a much more cost-effective implementation. An added benefit of this approach is that the 'rawer' sound of the Omni helped it 'cut through' in the mix of the pop songs of the times (in the same way that thin organ electronic sounds worked on 60s pop songs, rather than a Hammond). The PolyMoog, thanks to its two detuned MOs (along with FM and PWM), does provide sufficient complexity of tone to stand as an unaccompanied instrument.

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<sup>5</sup> <http://120years.net/buchla-synthesisers/donald-buchla-usa-1963/>

<sup>6</sup> a similar version with separate bass output

<sup>7</sup> eg in 'Moving in Stereo', 'All Mixed Up'



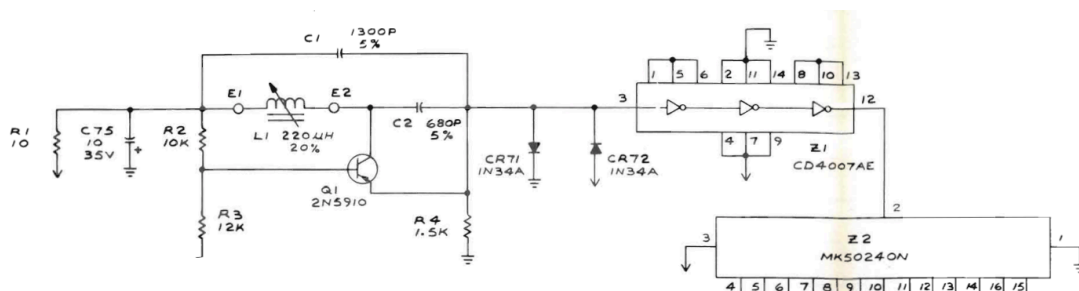


fig. 2. The Omni MO, buffer IC and TOS. Source: ARP Omni-2 Service Manual.

Rather than using integrated square waves to provide the tone source, The Omni differentiates the square wave (with a suitably long time-constant) then clips this signal with diodes to provide a suitable waveform.

The PolyMoog is capable of producing lush analogue sounds and is best known for the legendary 'Vox Humana' popularised by Gary Numan<sup>8</sup>. This sound is only available on the PolyMoog Keyboard which has a separate board exclusively to generate this preset sound. To get the exact sound used by Numan, the Direct output is used (Incidentally, the lower two octaves do not function if the Bass Filter switch is operated while using this output).

A comparison between the Omni and the PolyMoog is shown in appendix 3b.

The essence of a synthesizer is that there is user control over timbre and dynamics of the generated waveform. Early attempts at synthesis were monophonic as it was not practicable to implement this type of control for more than a single note at a time.

Japanese and USA manufacturers jostled throughout the 1970s to bring polyphony to the market. Multiple notes could be sounded on an Emu modular system due to a microprocessor controlled keyboard. This involved digital scanning of the keyboard, and then allocating any played notes to free voice channels. The system solved the problem of how to offer the best polyphony/features/cost ratio.

Overall, the PolyMoog was a significant development in synthesizer design. Moog's US Patent 4099439 clearly states that one intention of the instrument was to provide the feel and sound of a piano. This was by and large achieved. The PolyMoog has 71 notes, full polyphony, touch sensitivity, and a sustain pedal. By today's standards the piano preset sound is unconvincing, but measured against electric and electronic pianos of the time it would have held its place<sup>9</sup>. Bob Moog considered that the design was right: *'Polymoog, our most recent development, is an example of "musical engineering" at its finest...I'm convinced that Moog offers*

<sup>8</sup> eg in 'Cars', a No. 1 hit for Numan in 1979

<sup>9</sup> this was before sampled piano keyboards existed



*equipment that gives you the most quality, playability and musical control over sound.'* [2]

### The state of the electronics art in the 1970s

A question comes up when evaluating whether to repair vintage equipment: if several ICs have failed, what is to prevent more ICs going bad in the near future? If a significant number of failures is likely, then repair may be uneconomical.

The potential for ICs to have a high failure rate was identified early on, and the first symposium on the topic was held in 1962. By the time the PolyMoog was being manufactured most of the teething troubles<sup>10</sup> had been remedied. Other small-scale reliability effects were yet to present themselves (due to the introduction of nanometer scaling). It is reasonable to assume, therefore, that ICs made during this time (the late 1970s) are quite reliable. However, this period of manufacture was affected by failure due to environmental causes. In the late 1970s the main cause of IC failure was ionic contamination (from the plastic case), and this issue was related to the way integrated circuits were packaged and mounted on a PCB [3]. This raises the point of difference between semiconductors in use, and in storage.

A quote from Dubsounds states *"As is well documented the older ICs have a very thin substrate (insulation between internal transistors) and the substrate deteriorates with time so it's fully possible for an IC to fail even when not in use."*[4] This would seem at variance with the fact that modern ICs are made with smaller dimensions on the substrate. The internal transistors in an IC use layers of various semiconductor materials (Si, Ga, In) along with metals (Al, Au), and dielectrics (TiO<sub>3</sub>, Pb, Sr) to form quantum heterostructures. In modern ICs these layers may be only a few nanometers thick. Older IC technologies (TTL, CMOS) were large geometry by today's standards, so there should be less risk of inherent failure.

Semiconductor Reliability Engineer u/afcagroo [5] comments on Reddit that in the 1970s plastic IC cases replaced the very robust ceramic cases. These were prone to failure due to the ingress of moisture. In the late 1970s and early 1980s this problem was corrected by changing the elements used in earlier designs (such as As and Br) that lead to corrosion. This is a likely explanation why electronic equipment from the 1970s that has been in storage fails<sup>11</sup>. In New Zealand, the average relative humidity is 81% (range: 73% to 92%)<sup>12</sup> so there really is nowhere in the whole country to avoid exposure without storage in a climate-controlled room.

Other factors of aging (at the atomic level) occur so slowly as to not be of practical concern. The author has put many ICs that are over 40 years old into service without any problem. Notwithstanding moisture issues, it is expected

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<sup>10</sup> such as the Purple Plague

<sup>11</sup> notwithstanding that dried out electrolytic capacitors are also a major contributor

<sup>12</sup> data sourced from NIWA



that the shelf life of an IC would be > 100 years, as without voltage and temperature stresses there is little likelihood of failure.

Wyrwas [6] observes that one particular failure mechanism (hot carrier injection) happens at room temperatures, and failure analysis data from telecommunications equipment shows premature failure of ICs with a predicted life of 15 to 20 years.

Some ICs are now known to have a high failure rate. For example, the Roland Juno has six voice ICs (80017a) that are notoriously unreliable. This is also the case with the divider ICs used in the PolyMoog (MM5823). The reason is unclear. Unusually, this IC uses  $\pm 15\text{VDC}$  and this may make it more sensitive to any fluctuations or faults on the power supply rails. The purpose of the -15V is not specified in the data sheet, and the internal circuitry is not disclosed. Presumably it provides some form of biasing to the FETs.

Comments on the PolyMoog reliability are in Appendix 2.

The reliability of the PolyMoog PSU is covered in Section 3.



## Section 2 System Architecture and Circuit Description

For any troubleshooting and repair, it is necessary to understand the normal operation of any device. The intention of this section is to clarify and supplement the Moog service documents available. [7][8]

Description of the Power Supply is dealt with in Section 3.

### Overview

The PolyMoog uses a combination of monophonic and polyphonic circuit techniques to produce its sound. Several of these are unique to this instrument and Moog held patents on these: using a dual MO / TOS and divider system to obtain a chorus effect (USP4228717 and USP4145943), use of a special 'modulator' circuit block to respond to a velocity sensitive keyboard (USP4099439), and a combined monophonic/polyphonic keyboard (USP 4282787). It is helpful to study these documents alongside the PolyMoog Service Manual to gain an understanding of the system architecture.



fig. 3. Version indicator icons used in the service manual. Source: Moog Music.

An overview of the PolyMoog is given in section 1 of the PolyMoog Service Manual. Several block diagrams are shown, but a sense of self-evidence is presumed. Only by studying the circuits can one expect to understand the instruments architecture<sup>13</sup>. Some sections of the manual are common to both the synthesizer and the keyboard versions but not every detail will apply in both cases. Figure 1-1 (Page 1-10) shows the PolyMoog Flow chart. Although depicting both versions, the front panel filter gain controls are not present on the PolyMoog Keyboard. It also fails to indicate that the CONTROL INFORMATION lines also come from the keyboard. Figure 1-2 (page 1-11) shows the overall block diagram. An amended version of this drawing is shown in figure 4. There are two oscillator ranks providing square waves which are supplied to the voice cards. The output waveforms from there are square and sawtooth waves. The keyboard sends signals to the respective voice cards, as well as to the TL board, and the TR board.

<sup>13</sup> The Service Manual states "Due to the complexity of this instrument, no overall interconnecting wiring diagram exists." (section 1.3).



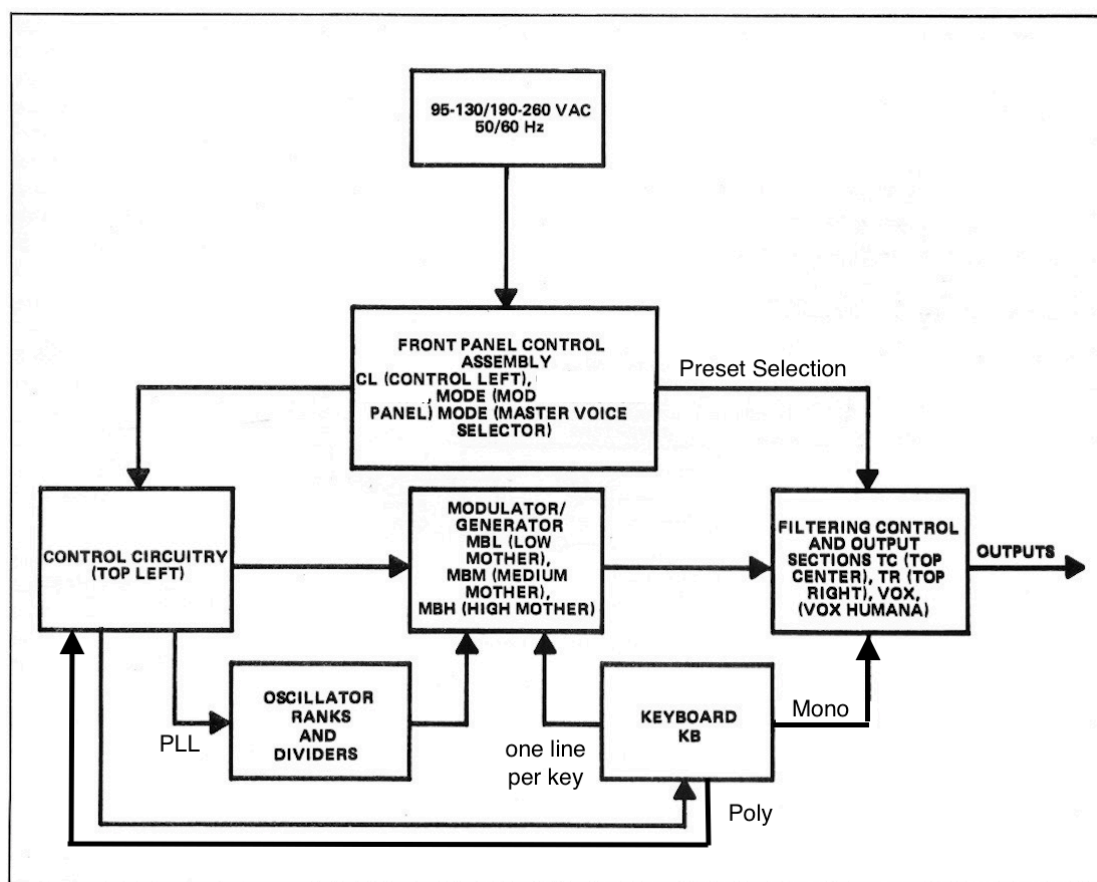


fig. 4. Block Diagram (after Moog Music).

### Mode Selection

The Mode (Preset) switches control the filter, envelope and modulation settings for each of the 14 sounds. The circuit is described in Section 7 of the Service Manual.

Control signals are encoded into binary and sent to the TR board. Here, they are decoded using CD4051 multiplexers. These decode the binary code and send it on 14 lines to 54 resistor networks. Thus, depending on the preset selected, a specific binary code is generated and a corresponding value of current is sent to the control circuits for ADSR and modulation functions. Details are shown in appendix 14.

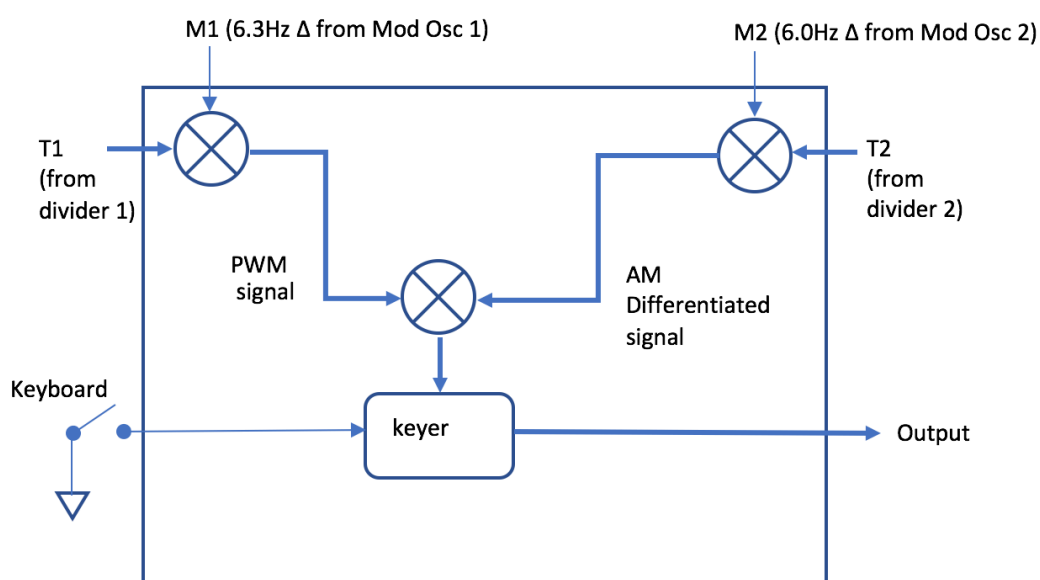
### Modulation Card

The Modulation Card (Voice Card) contains the most complex IC in the PolyMoog.

Each of the 71 notes is provided with a Modulation Card. These are housed in sockets on three motherboards. Each motherboard also contains a Balance Card, the purpose of which is to autocorrect for any level changes of the PWM and sawtooth signals when switching between presets.



Each Modulation Card takes a divide down signal from MO1 (T1) and MO2 (T2). These are summed together and sent to a VEM via a gating circuit controlled by the keyboard. T1 and T2 are respectively modulated with a separate LFO, as required. This produces a squarewave signal from T1 that can be pulse-width modulated, and a sawtooth wave from T2 that can be amplitude modulated. The arrangement is shown in figure 5.



*fig. 5. Modulation Card modulation routing.*

Each modulation card also has a VCA and VCF. A composite signal of DC plus a 20kHz carrier from the keyboard controls the dynamics (attack and decay rate, sustain level) and brightness (via a 2<sup>nd</sup> order LPF). The purpose of the VCF is to set whether there is a timbre variance with dynamics for each preset.

## Oscillators

The PolyMoog is unusual for a paraphonic design in that it has two MO circuits<sup>14</sup>. These supply two TOS circuits, but with a one semitone frequency offset. By using an additional ÷2 stage for the second TOS output a slightly different frequency can be derived. A TOS has a frequency error margin of greater than ±1 cent, sufficient to provides a slight detune when the two divider signals are combined. This produces a chorus effect.

<sup>14</sup> Korg later used a simplified version of this idea in the PE-2000, and Lambda



Note	Cent Difference
C8	0
B7	1.13
A#7	1.786
A7	2.035
G#7	1.943
G7	1.519
F#7	0.944
F7	0.13
E7	3.347
D#7	1.786
D7	0.172
C#7	2.048
C7	0

*Table 1. Typical Cents difference. Source: US Patent 4228717.*

The generator system is shown in figure 6. Two high frequency relaxation oscillators supply a square wave to two top octave synthesisers, which sends thirteen frequencies to the respective divider ranks. A PLL for each MO is used to control the frequency. Two reference oscillators of 1.2kHz control their respective MO's, and a similar frequency from the dividers is applied to the phase comparators. The tune control (Fine Tune) adjusts both reference oscillators by  $\pm 2$  semitones. The detune control (Beat) allows for adjustment of the second reference oscillator by  $\pm \frac{1}{2}$  semitone. Two LFO oscillators can be applied respectively to the two reference oscillators, providing FM. Phase modulation of one of the reference oscillators can also be applied to produce a chorus effect. Both phase comparators can also be fed from a single reference oscillator, thus eliminating any detuning effects. The primary reason for Moog using this generator system was to provide various modulation methods to give a chorusing effect. In the patent, it is also identified that an additional advantage is the long-term frequency stability of the PLL. Selection of a particular modulation combination is activated by the Mode circuits. Details are shown in appendix 14.



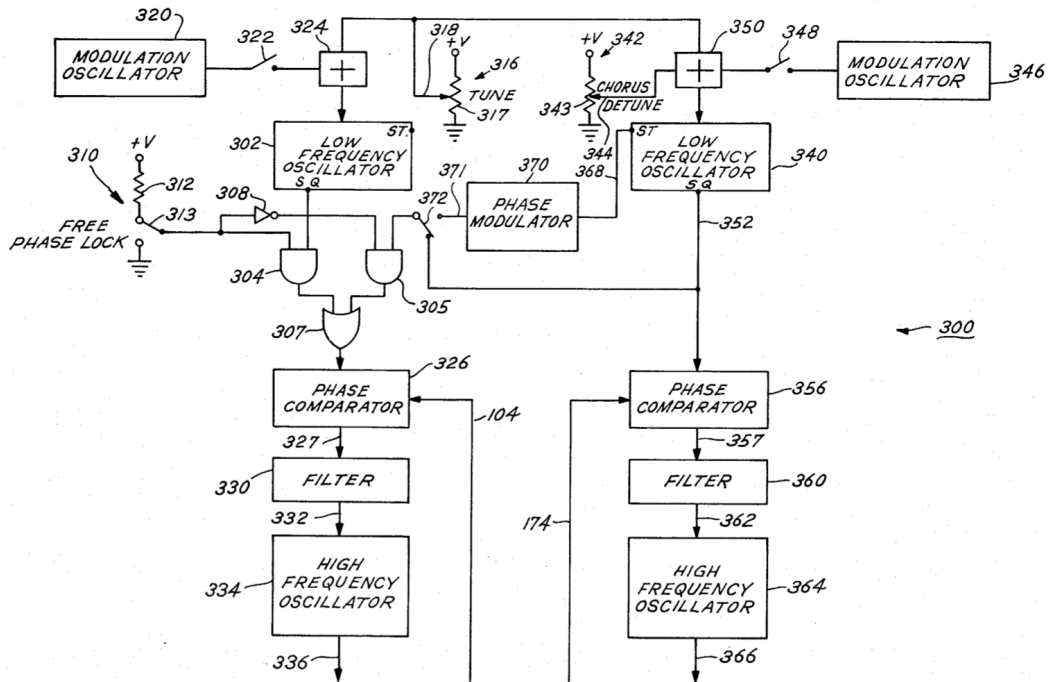


fig. 6. PLL / modulation system. Source: US Patent 4228717.

## Keyboard

The Keyboard control circuit consists of a polyphonic section and a monophonic section.

The monophonic section is a typical resistor ladder. The keyboard voltage goes to a sample and hold circuit via a bilateral switch which is activated by the keyboard trigger signal. This provides a CV output suitable for an external synthesiser. The arrangement is shown in figures 7 and 8.

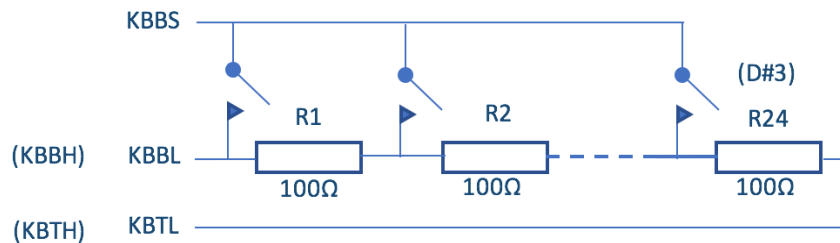
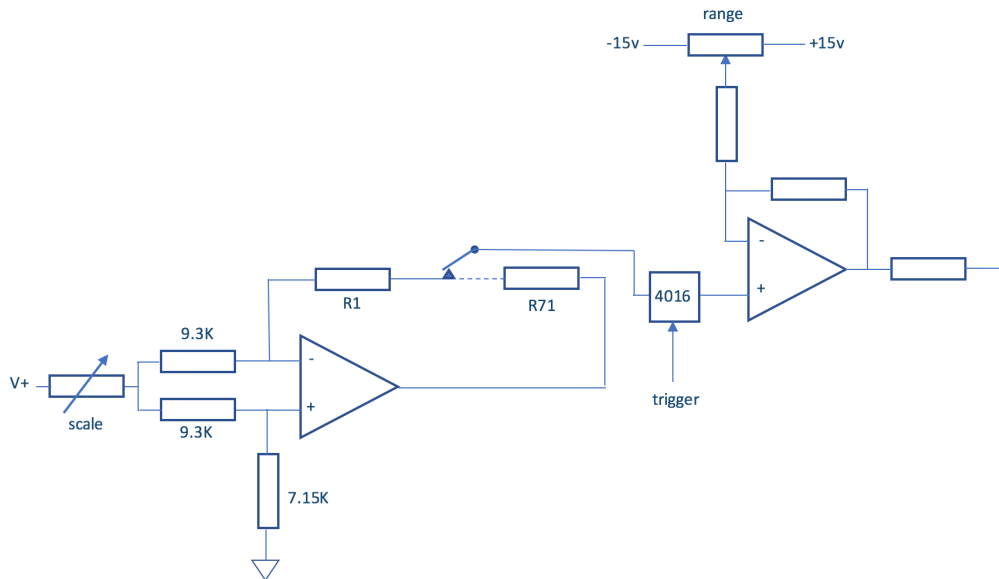


fig. 7. The monophonic keyboard circuit.

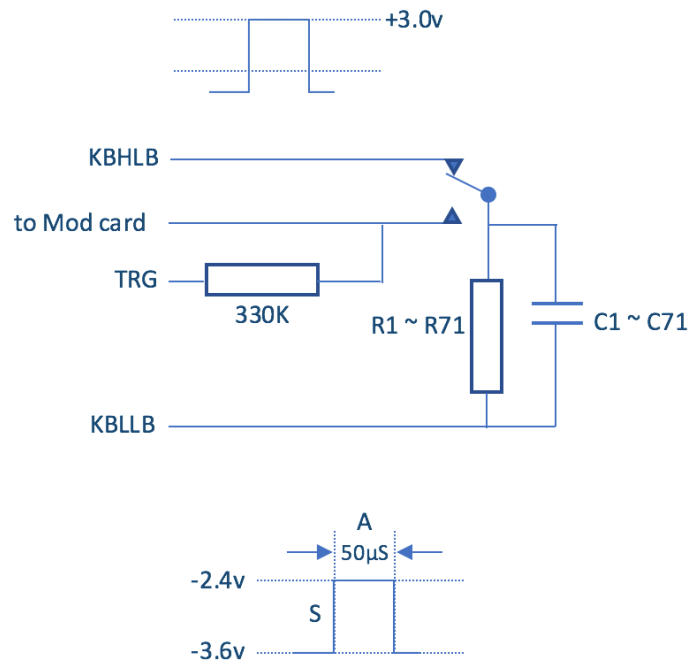




*fig. 8. Simplified circuit of the monophonic keyboard CV circuit.*

The Polyphonic section is comprised of individual gate signals sent to each modulator card via wires to the motherboards. It also contains a shared composite signal that is used to trigger the mod card filter and VCA as well as trigger the main VCF. When a key is depressed a 20kHz pulse wave from KBLLB is sent to the respective Modulator card. The attack time is controlled by the pulse width, and sustain level by the pulse height. DC from KBLLB is also applied to an RC circuit associated with each key. This is used to give velocity sensing thus providing keyboard dynamics. In this way attack, sustain, and dynamic information is superimposed on the one buss. A diagrammatic explanation of the interactions of these parameters is shown on page 4-5 of the Service Manual.





*fig. 9. the polyphonic keyboard circuit.*



The PolyMoog Keyboard that is the subject of this research is serial number 1642<sup>15</sup>. For this section, this number will be used to identify this specific instrument.

### The Power Supply

There are two variants of PSU used in PolyMoogs: Moog and Faratron. The topology of both is identical, but some actual component values differ. It is not unusual for a designer to sub-contract the PSU design and manufacture, probably because it is such a critical part of any electronic device. It seems in this case this was a mistake as the Faratron version was unreliable. Moog then designed their own version, and later model PolyMoog Synthesizers have it installed<sup>16</sup>. All PolyMoog Keyboards use the Moog PSU.

The PolyMoog power supply reputation for failure is not limited to the Faratron design, and 1642 had a dead PSU when purchased. The PSU regulator is a  $\mu A723$  based design. The 723 was released in 1968 and was the first voltage regulator IC. Before 3 terminal voltage regulators were available it was commonly used to provide voltage regulation in linear power supplies for low voltage applications (eg in the ARP 2600). It is still a listed component due to its versatile architecture. This versatility has also been its Achilles Heel as it requires more careful use than a 'plug and play' 3 terminal regulator.

The 723 is an adjustable voltage regulator with output voltages ranging from 2 to 37v. By suitable connection the voltage can be of either polarity. The output current is a mere 150mA, but this can be improved to several amps by using external transistors. The 723 contains four separate regulator building blocks which can be configured as desired by the designer (fig. 10). A shortcoming is that it has no internal circuitry to prevent excessive load current.

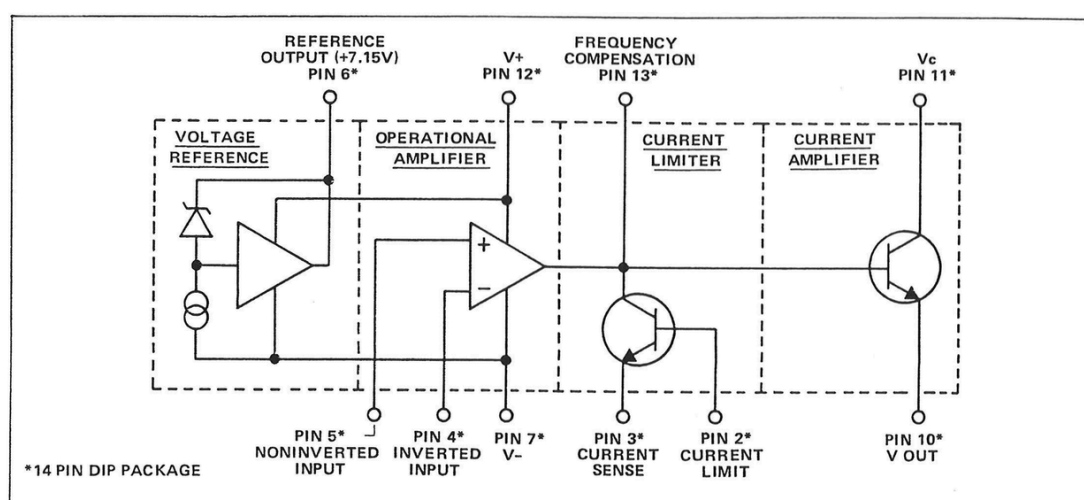


fig 10.  $\mu A723$  simplified schematic. Source: Moog Music.

<sup>15</sup> and on Mar 12, 1642, Abel Tasman was the first European to sight New Zealand

<sup>16</sup> above S/N 3200. This means about  $\frac{3}{4}$  of PolyMoog Synthesizers used the Faratron PSU



For those interested in learning more about the  $\mu$ A723, *The Art of Electronics*, 3<sup>rd</sup> Ed. [9] is recommended.

Moog used the same PSU design in the MemoryMoog, with a few minor design changes. In the PolyMoog, the total current on the  $\pm 15\text{V}$  supplies is limited to 0.75A (on the MemoryMoog it is 1.5A). Both have the +5V supply limited to 1.5A. There are 256 ICs, as well as several LEDs. The LEDs, Polycom ICs and TTL ICs will be drawing several milliAmperes each. This requires external pass transistors (MPSU05 and TIP41) in the PSU and these are in a Darlington configuration. By today's standards the PSU is fairly basic, but does provide current limiting (initiated by a 0.6V voltage drop for the  $\pm 15\text{V}$  supply, and a 1.2V drop for the +5V supply).

The most probable cause of failure is transistors overheating due to being pushed outside their SOA when the temperature gets too hot. The power transistors are mounted on an angled aluminium slab. This then is bolted to a metal subframe that runs the length of the PolyMoog at the rear. Thermal paste is applied at this junction. There is limited thermal conduction available as the subframe is lightweight and without heatsink fins, so overheating is a possibility. An improvement can be made by cutting a hole in the case below the PSU to allow for ventilation. It is also recommended to add a line filter to the mains input as it has no suppression whatsoever. Presumably there was less electrical interference in the 1970s. Owners would be advised to have a mains filter installed.

Troubleshooting the PSU is reasonably straight forward. The 723 ICs are socketed to provide easy replacement, if required. All three supplies use the 723 in the same standard configuration. However, there are a few points to note: the PSU sensing rails leave the PSU board and are terminated on the CL board, where the PSU voltages are distributed. This means that removal of the PSU connector will cause no output voltages, even on a healthy PSU. The other thing to note is that whereas the +5V supply is independent, the 723 for +5V supply derives its power from the +15V supply (as it needs at least 9.5V to operate). To test the PSU voltages, connections between these terminals of the PSU connector will need to be made:

supply	link			
+15V	1	2		
	3	4		
-15V	6	7		
	8	9		
+5V	12	13	8	9
	14	15		

Table 2. PSU supply and sensing lines pinout.

A further consideration is the Tranzorbs (transient voltage suppressors). These are located on the CL board. During troubleshooting it is often useful to remove power from some of the boards. On the PolyMoog this can be problematic as the  $\pm 15\text{V}$  supply Tranzorbs are 16V types. With less than normal load the PSU voltages can exceed this limit and the Tranzorbs will shunt the PSU rails. This



was the case on 1642. As a precaution, the three Transzorbs that protect the three main supply rails were replaced. These P6KE type devices have a 600W peak power rating. Maximum peak current therefore diminishes with a higher breakdown rating, but is still 26.7A for the 16 volt version.[10] The wording of their purpose in the PolyMoog Technical Service Manual (*...should a power supply overvoltage occur.*) is somewhat misleading. They are intended to stop transients appearing on signal and power lines and will not accept their rated current for prolonged periods<sup>17</sup>. The CL board is located in a difficult position and the front panel needs to be removed to allow access. On 1642 a slight modification was necessary for reassembly; the board mounting holes needed enlarged to allow for correct positioning, so that the PRE and VAR switches did not bind on the front panel.

The -15V supply was not working when I first obtained 1642. This was due to the failure of the MPSU05 transistor. This first repair occurred some 20 years ago when I was living in a small remote town, so I used a transistor on hand as a substitute. This was a BD139 which is an audio driver/small amplifier output device but can be used in this PSU as it has similar specifications, as they apply here. Today, a direct replacement is available from Central Semiconductor (the CEN-U05).[11] I have not replaced the BD139 as it is suitable for this undemanding application. The lower maximum current is of no concern as the TIP41 conducts the main current (0.75A). Once the PSU is functional it is advisable to replace all electrolytic capacitors. Output voltages can be trimmed with the presets on the board to within a tolerance of  $\pm 10\text{mV}$ . The pre-regulator DC voltages were checked for ripple and found to be within tolerance (readings were 1.2Vpp for  $\pm 15\text{V}$ , and 1.0Vpp for +5V).

	MPSU05	BD139
$V_{\text{ceo}}$	60V	80V
$H_{\text{FE}} (\text{max})$	125	250
$I_{\text{CBO}}$	$0.1\mu\text{A}$	$0.1\mu\text{A}$
$V_{\text{CE(SAT)}}$	0.4V	0.5V
$I_{\text{C}}$	2.0A	1.5A
$P @ T_{\text{A}} = 25^{\circ}\text{C}$	1.0W	1.25W

Table 3. Q2 parameter comparison.[12][13]

The other problem with the power supply was failure of two local smoothing capacitors. One of these was on the TR board, the other on one of the MO boards. On both occasions, they went short circuit when they failed, causing V+ or V- to shut down. This resulted in making all audio circuits inoperable. These capacitors are tantalum type and are prone to failure when exposed to voltage spikes. All the local board capacitors were replaced as a precaution (TL, TC, TR, MO). Fault-finding this condition is straightforward with symptoms being no audio output, but the LED and preset selection still functional (as  $V_{\text{cc}}$  is unaffected). Boards can be depowered one by one until the fault is located.

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<sup>17</sup> peak current handling reduces to  $< 0.67\text{A}$  by 4.0mS (with temperature derating)



To conclude this section a brief mention of other aspects of the power supply is given here. The  $\pm 15\text{V}$  and  $+5\text{V}$  rails are delivered to the CL board. Reticulation to all other boards is from this point. On the CL board a  $-5.5\text{V}$  supply is derived. It is used in the trigger circuit on the TR board. The PolyMoog circuit diagram also shows distribution of  $V_{\text{CHR}}$ . In the PolyMoog Synthesizer this is a regulated voltage of  $4.85\text{V}$ . The PolyMoog does not have this and  $V_{\text{CHR}}$  is  $5\text{V}$ .  $V_{\text{CHR}}$  is used as a common rail for audio (eg on front-panel potentiometers) instead of an earth.

### Mode Selection

This section of the PolyMoog uses TTL ICs to send preset selection signals to the display and TR board. A 74148 binary encoder outputs a three bit code corresponding to buttons 1 to 14.

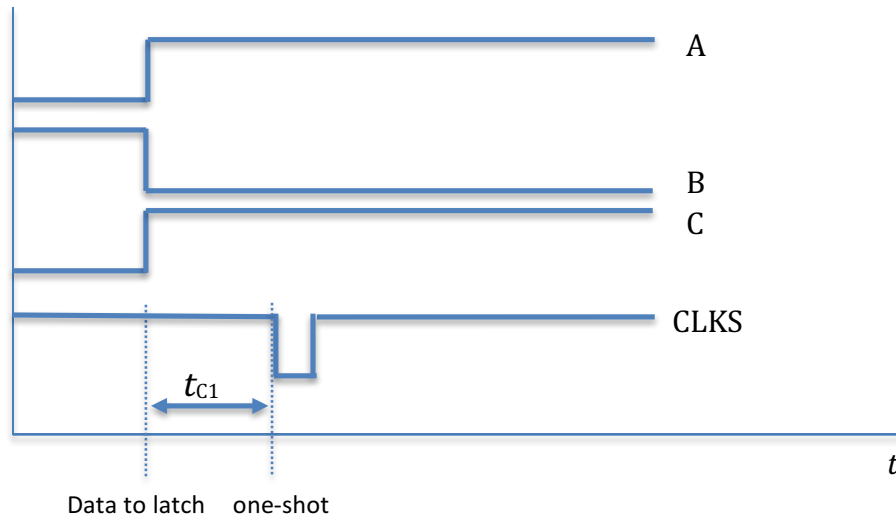
preset no.	binary code	tens bit	MSB state
1	001	H	L
2	010	H	L
3	011	H	L
4	100	H	L
5	101	H	L
6	110	H	L
7	111	H	L
8	1000	H	H
9	1001	H	H
10	000	L	L
11	001	L	L
12	010	L	L
13	011	L	L
14	100	L	L

*Table 4. Binary to decimal encoding.*

This section of 1642 was functional when I purchased it 20 years ago, but failed soon after the PSU was running again in 2018. The problem was traced to a dead 7413 IC. The purpose of this IC is to take the EO output from the encoder and provide a one-shot (a delayed  $10\text{ }\mu\text{s}$  pulse) to the clock input of a 7475 quad bistable latch.

The 7413 is a dual 4 input Schmitt-trigger NAND and on the Mode board both gates are used as inverters with 3 inputs tied to  $V_{\text{cc}}$ . It is interesting that actual NAND gates were not used. Perhaps it was due to which components were on hand (from bulk purchasing). While waiting on a 7413 to arrive I did get the circuit working with a 7400. The final solution was a 74LS13 as the 7413 is hard to source. The LS range is fully compatible with the 74xx range and it is a good idea to replace with them to lower power consumption.





*Fig. 11. Timing of the 7475 data latch.*

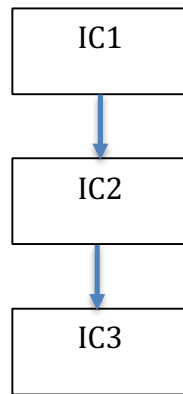
### Divider Circuits

A significant amount of repair time was spent on this section of circuitry. There are 24 MM5832 ICs used to divide the MO frequencies down to audio frequencies corresponding to each note. There are three possible solutions for repair: sourcing NOS, designing a new equivalent circuit for each faulty IC, or purchasing a replacement from Flatkeys.[14] In hindsight, this would have been the preferred option. To source a number of NOS MM5832 is difficult, and the price is formidable. An eBay search showed a price of \$US50 for a single IC, with a second site offering some for \$US120 per IC.

A difficulty arises in troubleshooting the PolyMoog. There are two probable causes of a dead note: a faulty voice card, or a faulty divider IC. If a note is not working at all this is not so problematic as voice cards are interchangeable so swapping will help prove where the fault lies. Before embarking on this test method it is recommended to clean all card contacts with isopropyl alcohol.

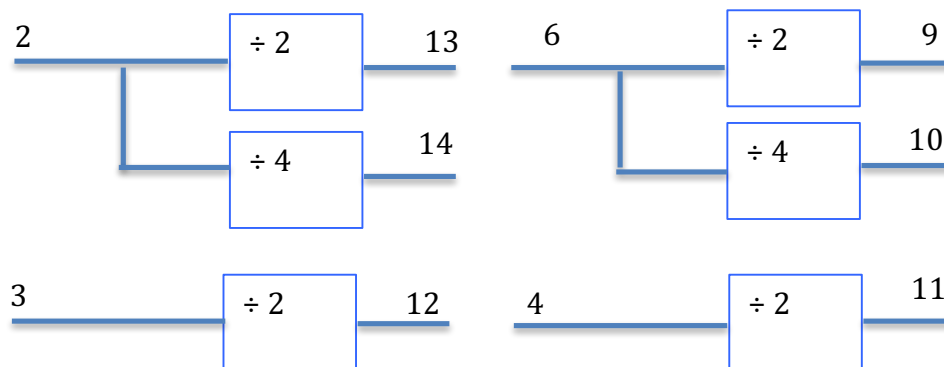
It was found that a substantial number of notes were faulty, with 23 keys either without sound, or sounding incorrectly. The reasons were several: intermittent key contact faults, voice card faults (dead voice cards), and divider circuit faults. The divider circuit IC faults can only be located one at a time. This is because the MO frequency cascades through banks of three ICs which are soldered onto the divider board. The problem is illustrated in fig. 12.





*Fig. 12. The MM5382 ICs are daisy chained. If IC one is dead, there is no way of predicting if IC2 or IC3 are also dead.*

Unable to ascertain the size of the divider fault problem I optimistically thought it would be one or two IC dead. On this basis making replacement circuits seemed feasible. As it turned out, eight ICs needed replaced, which took some time. The MM5823 is a purpose-built frequency divider for use with a keyboard TOS. It provides dual  $\div 2$  and  $\div 4$ , as well as an additional two  $\div 2$  circuits.[15] This makes it an ideal solution for a TOS system. Twenty four ICs are used in the PolyMoog (12 per MO/TOS). It uses PMOS logic running at +15V so from that aspect substitute dividers are not a problem. The closest standard CMOS IC is the CD4520 dual binary up-counter, which contains two four-stage D type flipflops.[16]



*Fig. 13. MM5823 configuration.*

To implement the MM5823 functionality two CD4520 are required. This is somewhat wasteful as they are 4 stage counters. They are readily available at low cost. The two ICs must be housed on a separate board. In the case of 1642 this sits perpendicular to the divider board.



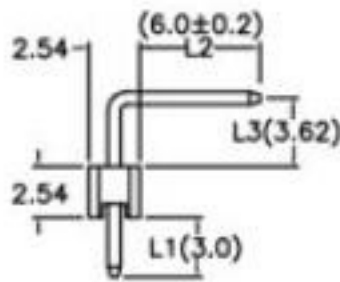


Fig. 14. Header pin dimensions. Source: <https://www.pololu.com>.

The two 4520 ICs are on small Veroboards which attach vertically onto the Moog board using 90° header pins. Ribbon cable is used to make the additional connections between the boards. The first version had two CD4520 ICs mounted horizontally on the board. Next, I tried a longer board with the ICs mounted vertically. The purpose was to try to find a layout that reduced wiring time. The longer design was easier to assemble but used more straps, so there was no gain in time. I also discovered that the IC sockets made the sub-assembly slightly too thick to allow the divider board wiring loom plugs to fit. Since these are CMOS ICs, ideally, they would be socketed but it may be necessary to solder them to the board, as was the case for 1642.

With multiple divider IC failures, there will likely be more than one fault indication. Some keys will have no output, some will play in the wrong octave<sup>18</sup>, others will have seeming tonal, volume, or modulation issues. Some problems showed up on some presets only. This is logical once it is realised that the modulation and envelop functions are configured for each preset. It is therefore recommended to tackle any dead divider ICs before troubleshooting further.

<sup>18</sup> this is due to the left MO output being 1 octave lower than the right MO.



MM5823			CD4520			wiring		
pin	designation	function			pin	MM5823	4520a	4520b
1	V <sub>gg</sub>	?, -15v	CP1		1	1 NC		
2	Input 1		Not CP1	enable	2	2	1	
3	Input 2		Q1-0	÷ 2	3	3	9	
4	Input 3		Q1-1	÷ 4	4	4		1
5	NC		Q1-2	÷ 8	5	5 NC		
6	Input 4		Q1-3	÷ 16	6	6		9
7	V <sub>dd</sub>	earth	MR1	reset	7	7	8, 7, 15	8, 7, 15
8	V <sub>ss</sub>	+15v	V <sub>ss</sub>	earth	8	8	16, 2, 10	16, 2, 10
9	Output 4a	÷ 2	CP2		9	9		11
10	Output 4b	÷ 4	Not CP2	enable	10	10		12
11	Output 3	÷ 2	Q2-0	÷ 2	11	11		3
12	Output 2	÷ 2	Q2-1	÷ 4	12	12	11	
13	Output 1a	÷ 2	Q2-2	÷ 8	13	13	3	
14	Output 1b	÷ 4	Q2-3	÷ 16	14	14	4	
15			MR2	reset	15			
16			V <sub>dd</sub>	+15v	16			

Table 5. IC pinouts for the divider IC replacement.

### Other faults

Several other minor faults were discovered and repaired:

- Four of the PRE / VAR LEDs had failed and were replaced.
- All Voice Card connectors were cleaned with IPA.
- One of the keys had a broken tine (which holds the key in position when at rest). The repair was to fabricate an aluminium bracket and bolt this to the keyboard sub-frame. This is a known problem and is mentioned in the PolyMoog Service Notes (1207-33). The factory solution was to add a stop bar on later instruments.
- Some keys were operating intermittently. Affected key contacts were cleaned with CO cleaner. Ideally all key contacts would be adjusted but without the special Moog keyboard adjusting tool this would be a difficult procedure. To get the response of all keys back to perfect operation would require considerable time and care. It may be worthwhile, as the 'feel' of the PolyMoog keyboard is very good. The Moog Service Notes (993-042314-004) state that 'Mechanical tolerances in PolyMoog keyboards are very critical for they directly affect keyboard dynamics'.
- Several rubber key bushings were replaced.
- A missing slider knob was replaced.
- An intermittent loss of power to the PolyPedal was due to a dirty Cinch Jones connector. This was cleaned.



- Most of the slider potentiometers were stiff to operate. One was disassembled for examination. This established that the nylon wiper bush was binding due to hardened lubricant. CO Contact cleaner was applied to free the sliders.
- The top C# note eventually gave signal leak-through with the Mod card in place. The top two cards were removed.

### Calibration

A full calibration was undertaken once the instrument had been powered for one hour. Most tests were still within specification, with the exception of some of the tuning settings: standard pitch, and fine tune zero position. One calibration test was not able to be performed: the Phase Modulation amount did not show any change to the pulse width when R100 was adjusted. It is unclear why this was. Most of the calibration is done on the TL board. On the TC board there are three parameters to setup. The filter cutoff, the Swell range, and the Harpsichord tone. The latter is not mentioned in the service manual, but is adjusted with R42. Some parameters require setting to a tolerance of  $\pm 5\text{mVDC}$  so a DVM with sufficient resolution is required.

### Factory Modifications

1642 was checked for all relevant modifications. Most of these had been done, either in service or at the factory. Missing was one that puts a  $1\text{M}\Omega$  resistor from earth to the PLL line into the MO, so this was added. The MO boards installed in 1642 are the redesigned version 2. On the circuit diagram the  $1\text{M}\Omega$  resistor is shown as a requisite component for this version, however this was only fitted from serial number 1693 on. This modification prevents chirps in the MO caused by coupling between the PLL and the MO. An interesting discovery was that although the date inside the lid was 11/78 the filter circuit board is dated 3/79. There are two plausible reasons for this: 1642 was in the factory for several months, or the TC board was replaced at some time.



## Summary of Findings

1. The chance of finding a PolyMoog in full working condition is very small (see Appendix 2).
2. These days it is potentially much easier to repair vintage equipment, thanks to the Internet. This hopefully provides company service information, sources of parts, and helpful forums.
3. The PolyMoog exhibits typical small production run electronic engineering for the era. After this time manufacturers produced synthesizers using specialised LSI circuit design.
4. As a result of this pre-LSI technology being used, understanding of circuit function and obtaining available replacements is generally possible<sup>19</sup>. There are some exceptions in the PolyMoog: the proprietary voice IC makes it difficult (or very expensive) to replace as they can now only be cannibalised from another PolyMoog, or sourced from a scarcity of NOS. On the other hand, as the voice cards plug into the Motherboard it is easy to put dead cards on the extremities of the keyboard.
5. Supplies of most of the active electronic components are good. Prices and delivery costs do vary considerably. Some NOS is still available. As both the 7400 series and 4000 series logic ICs were mass-produced for a long period the possibility of obtaining them is good. However, certain specific ICs in these ranges are becoming rare. All the opamps used in the PolyMoog are still available. OTA's are now difficult to obtain. A few specialised ICs are very difficult to source, namely the MM5823N, MK50240P,  $\mu$ A726, CA3094, D16P1, MPSU05, 4051AE, Polycom V DM7670, and the Polycom II DM8670. The possibility of getting no-name ICs is good but it is dubious whether they are as reliable. In circuits where tolerances are important it is unlikely that knock-off ICs would function correctly.
6. The technical documentation supplied by Moog for the PolyMoog is comprehensive and reasonable good. A large number of modifications are documented in Section 2. There are few errors, and descriptions of operation are sufficiently detailed to enable an experienced repairer understand the circuitry. The published scanned documents do lack some quality and some are too small to read without enlargement. Although there are some block diagrams, it takes some time to understand exactly what everything does, and how all the sections of the PolyMoog fit together. This is partly due to the documentation lacking some connection details, and also to some functional blocks being spread across several boards (sometimes in an illogical manner).
7. The overall construction of the PolyMoog is good, with a heavy solid keyboard. Whereas it is possible to repair electronics that are housed in cheap plastic, there is something satisfying about repairing something that was built to last.
8. Time required to repair / restore a PolyMoog will be considerable. This is due to both the complexity and the fact that it was never a reliable design. This means that there will be multiple faults to trace and fix.

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<sup>19</sup> many vintage synths used 3<sup>rd</sup> party proprietary ICs (eg CEM, SSM). Since 2016 some of these are being remanufactured



9. The competence level required to tackle a PolyMoog is high. Due to the overall complexity of the design it requires an experienced technician. Some advanced knowledge of digital and analogue circuit techniques is needed to diagnose, repair and calibrate all parts of the instrument. This assumes availability of the test equipment listed in appendix 10.
10. Access is an important part of any repair process. The PolyMoog is generally very good in this respect. The cover is easily removed making the three top boards easily accessible. Most connections are on Molex connectors, so there is little or no soldering involved to remove a board. These boards hinge to allow access to the motherboard, and the voice cards and MO cards are socketed allowing easy removal. The CL and Vox Humana boards are not readily accessible, as they are tucked under the front panel.
11. Viability of repair is usually related to the value of the item. In the case of the PolyMoog this is now quite high. Further to point 8, for an enthusiast who is a PolyMoog repair novice, considerable time will be spent in finding their way around this synthesizer. It is expected that at least 50 hours will be required. If a professional is employed the time may be no less, but a full refurbishment could be expected. As well as repairs, this would entail replacement of all electrolytic capacitors, all modifications performed, full calibration, all key responses set, and cosmetic details as needed to bring the instrument up to 'as new' condition.
12. It should be noted that repair is not the same as restoration or refurbishment. The PolyMoog front panel is quite durable and should generally not need much attention. The keyboard is a different matter. Extra time will be needed to achieve identical response from every key.



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## Appendices

1. A short biography of the career of Dave Luce
2. PolyMoog Reliability
3. a) PolyMoog and PolyMoog Keyboard Differences  
b) PolyMoog Keyboard and ARP Omni II Comparison
4. Active Components List
5. List of Abbreviations
6. IC Manufacturers Chronology
7. Component Suppliers
8. Parts Suppliers – Component Price & Shipping Cost Comparison
9. IC Manufacturer Prefixes
10. Test Equipment Used
11. Synthesis Circuit Topologies used in the 1970s
12. Repair Assessment Chart
13. The PolyPedal
14. Parameter Settings for the Presets
15. Synthesizer Terminology
16. Polyphonic Synthesizers of the 1970s – early 80s



## Appendix 1

### Dave Luce (1936-2017)

While researching this topic I came upon the fact that Dave Luce died last year. A short recount of his career is presented here.

Dave Luce was the designer of the PolyMoog. His exceptional ability with electronics gained him a position with Moog Music in 1972, where his role was to develop this polyphonic synthesizer.

*“Following the Polymoog, he headed the Engineering Department at Moog, became president in 1981, and a co-owner in 1984. In these capacities, he was directly involved with and oversaw the development of many other instruments, including the Micromoog, the Mutlimoog, the Moog Taurus, the Moog Source, the Moog Liberation, and the Memory Moog.”<sup>20</sup>*

In 1987 Moog closed down, and he accepted a senior R&D position at American Optical, now called Reichert Technologies. Here he began research on the Noncontact Tonometer (NCT), a device which utilizes the response of the eye to an air puff to measure the pressure in the eye as a means to detecting the potential onset of glaucoma.

In 2000, he discovered a means to disentangle the effects of the viscoelasticity of the cornea from the pressure inside the eye, thereby vastly improving and extending the diagnostic capability of the instrument, which was renamed the Ocular Response Analyzer. His new measurement method is called Corneal Hysteresis.

This last phase of his scientific career is of personal interest, as I have an inherited risk of glaucoma, and get tested bi-annually.

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<sup>20</sup> <https://www.forevermissed.com/david-alan-luce/#lifestory>



## Appendix 2

### PolyMoog Reliability

It is not hard to find anecdotal evidence that the PolyMoog is complex and unreliable. Here is a selection of comments:

*"The PolyMoog's biggest problem, however, was reliability. Basically, it didn't have any!! It is reputed to be perhaps music history's most unreliable synthesiser and most of them spent more time in service centres than studios!!"*<sup>21</sup>

*"The Moog Polymoog — now a servicing nightmare."*<sup>22</sup>

*"Polymoogs are one of those synths that are almost infinitely better on paper than they are in real life. Oh yeah, they sound HUGE, but actually getting them to make that sound reliably? Nightmare is a very appropriate word!"*<sup>23</sup>

*"This polymoog was one of the most challenging units I ever worked on. The circuit design is complicated and not at all intuitive or familiar."*<sup>24</sup>

*"If I could give it a minus 20 I would. The Polymoog is always breaking down. Watch ebay, 4 out of 5 polys sold are broken in some way. The poly is difficult to repair. In part because of the convoluted design, and mostly the inavailability of specialty (OEM) parts such as the "polycom chip" and the MM 5328 divider chips. Most repair shops won't touch them."*<sup>25</sup>

*"I'd rate mine at 7 maybe 8 on the reliability scale [of 1-10]. If you've seen my previous posts I had her all working after my PSU incineration and then she melted an IC on the CL board for no apparent reason, other than maybe age? Not a good sign for the future !!!"*

*"Overall reliability rating varies. If you know how to work on it: 7. If you can afford to keep it well maintained and never move it: 6. If it is not well maintained, or it you move it around a lot: 4."*<sup>26</sup>

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<sup>21</sup> <http://www.hollowsun.com/nostalgia/vintage/polymoog/index.html>

<sup>22</sup> Analog Synthesizers - Mark Jenkins. 2007

<sup>23</sup> <https://www.reddit.com/r/synthesizers>

<sup>24</sup> <http://fixingelectronics.blogspot.com/2013/05/polymoog-repair.html>

<sup>25</sup> <http://www.harmonycentral.com/reviews/product/moog-polymoog/619052>

<sup>26</sup> <http://dubsounds.proboards.com/thread/2623/polymoog-reliability-all>



A PolyMoog owner's directory has been set up on the Dubsounds website<sup>27</sup>. Here 82 PolyMoog Synthesizers and 44 PolyMoog Keyboards are listed. A rating (out of 10) for 'Condition', and a 'Last Restored' column are included. From these, and comments, the average state of PolyMoogs can be surmised. The average condition rating for this sample of 126 instruments is 7.06/10.

Given that 51 (41%) of these Polymoogs have already been restored this is a fairly low rating for reliability. Several of the listings put a 'not working' comment alongside a condition rating of 7 or 8 (indicating the physical condition is good but the keyboard is non-functional), so the overall reliability is therefore somewhat less than 71%.

@moogpolymoog on Facebook recounts the story of finally getting a PolyMoog working after several years (and several technicians) of fault finding.<sup>28</sup>

There is sufficient anecdotal evidence to show that the problems encountered with 1642 are not an isolated case. In order to make the PolyMoog sound like a synthesizer, rather than an organ, the design became quite complex. This resulted in a shorter MTBF.<sup>29</sup> However, not all faults can be put down to design complexity. The divider ICs were simply prone to long-term failure (Moog could not have predicted this). The primary point of failure seems to be the PSU. The decision to initially use a third-party supplier may have been driven by marketing demands, rather than good engineering practice.

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<sup>27</sup> [http://www.dubsounds.com/pm\\_owners.htm](http://www.dubsounds.com/pm_owners.htm)

<sup>28</sup> [https://www.facebook.com/pg/moogpolymoog/notes/?ref=page\\_internal](https://www.facebook.com/pg/moogpolymoog/notes/?ref=page_internal)

<sup>29</sup> Mean Time Between Failure



## Appendix 3a

### PolyMoog and PolyMoog Keyboard Differences<sup>30</sup>

	PolyMoog	PolyMoog Keyboard
Years of Manufacture	1975-80	1978-80
Price	\$5295 USD	\$3000 USD
Vox Humana preset	No	Yes
Audio Reference Voltage	+4.85V	+5V
CR board	Yes	No

## Appendix 3b

### PolyMoog Keyboard and ARP Omni II Comparison

	Omni II	PolyMoog Keyboard
no. of keys	49	71
cost	£1200 (1975)	£2295 (1978) <sup>31</sup>
TOS IC type	1 x MK50240N	2 x MK50240P
divider IC type	CD4520	MM5823N
no. of ICs	81	256
touch sensitivity	sets release time	sets dynamics
envelope controls	ADSR	attack
attack time response	first note only	all notes
filter ADSR controls	Yes	No
envelope trigger	multiple	single / multiple
bass split	Yes	Yes
layering	Yes (synth + strings)	No
foot pedals	Yes	Yes
Phaser	Yes (3 x MM3002 BBD)	No
Presets	No	14
Pitch Controller	No	Ribbon

<sup>30</sup> The original synthesizer was named PolyMoog Keyboard. This changed to PolyMoog Synthesizer, when the preset version (which took the name PolyMoog Keyboard) was released.

<sup>31</sup> [http://www.dubsounds.com/pm\\_history6.htm](http://www.dubsounds.com/pm_history6.htm)



## Appendix 4

### Active Components List

Item	Board											
	TL	TC	TR	HF Osci	Divider	Mode	CL	PSU	MBs	bal	vox hum	totals
board no.	7	8	9	1 & 2	3	12	10	13	4,5,6	& voice	14	
Op Amps												
LM358N	15		7							6		28
MC1458CP-1	3	13	4						3		2	25
741	3	1					1					5
3130	4											4
726	2											2
LF353		1										1
CA3094		1										1
TL082			1									1
LF356N			1									1
LM3080AN	8											8
Transistors												
2N3904		1	8	2		2						13
2N3906		2	2	2								6
2N3392		6										6
D16P1				2								2
TIP30							1					1
TIP41								4				4
MPSU05								3				3
TTL												
7413	1			2		1						4
7426	1		2	2		2	1					8
7401							1					1
7473				2								2
74148						1						1
7475						1						1
7447						1						1
CMOS												
MM5823					24							24
4007	2		2									4
4011	2											2
4046	2											2
4051BE		2										2
4016AE			3				1					4
4051AE			6									6
4052B				2								2
MISC												
CA3046		1										1
723								3				3
MK50240P				2								2
MAN6630						1						1
Polycom V DM7670										71		71
Polycom II DM8670										3		3
												256



## Appendix 5

### List of Abbreviations

MO	Master Oscillator
TOS	Top Octave Synthesizer
PLL	Phase-Locked Loop
OTA	Operational Transconductance Amplifier
Op amp	Operational Amplifier
VEM	Virtual Earth Mixer
CMOS	Complementary Metal-Oxide Semiconductor
TTL	Transistor-Transistor Logic
PSU	Power Supply Unit
MOD	Modulator (Voice) Card
CL	Left Control Board
DIV	Divider Board
MBL(M)(H)	Motherboard Low (Medium) (High)
MODE	Preset selector
TC	Top Centre Board
TL	Top Left Board
TR	Top Right Board
$V_{CC}$	+5V <sub>DC</sub>
$V_{CH}$	Audio Reference Voltage
$V_{+}$	+15V <sub>DC</sub>
$V_{-}$	-15V <sub>DC</sub>
SOA	Safe Operating Area
PCB	Printed Circuit Board
NOS	New Old Stock
LSI	Large Scale Integration
Voice	A signal channel assigned to a single note
PWM	Pulse Width Modulation
FM	Frequency Modulation
LPF	Low Pass Filter
LFO	Low Frequency Oscillator
CV	Control Voltage



## Appendix 6

### Semiconductor Manufacturers Chronology

Many IC manufacturing companies have been subsumed into larger companies. Current companies are shown on the left. The year of acquisition is shown in brackets. Those who made ICs for the PolyMoog are shown in bold type.

Analog Devices (2016)

Linear Technologies

---

ON Semiconductor (2016)

**Fairchild**

---

Renesas (2017)

Intersil (1999)

**Harris (1988)**

**RCA**

---

Maxim

---

Microchip (2015)

Micrel

---

**Texas Instruments (2011)**

**National Semiconductor**

---

NJR

---

Rohm

---

NXP (2015)

**Motorola**

**Philips Semiconductor (1975)**

**Signetics**

---



## Appendix 7

### Component Suppliers

In general, supplies of 4000 series CMOS and 74xx TTL are slowly drying up. However, many types in each series are still readily available, as are most of the op amps. The hard to get items are shown here.

Item	Used in	Quant.	Suppliers	Lowest cost (Feb '18)
μA726 op amp	TL board	2	UT Source Portabellabz* Vintage Synth Parts	unknown 10eu
CA3094 op amp	TC board	1	UT Source	\$US2.15
LM3080AN op amp	TL board	8	Futerlec	\$US1.90
D16P1 transistor	HF osc	2	UT Source	unknown
MPSU05 transistor	PSU	3	Donberg	13eu
SN7413 TTL	TL, HF, mode	4	Futerlec	\$US0.95
MM5823 CMOS	Divider	24	Flat Keys*	£12.30
CD4051AE CMOS	TR board	6	UT Source	unknown
CA3046 tran. array	TC board	1	Futerlec	\$US1.10
MK50240P	HF osc	2	Vintage Synth Parts	31eu
Polycom V DM7670	Voice card	71	None known	
Polycom II DM8670	Bal. card	3	Vintage Synth Parts	39.95eu
Potentiometer knobs	Front panel		Syntaur	\$US2.95
Key bushing	Keyboard	71	Syntaur	\$US0.70
			*equivalent	

### Suppliers List

#### General

RS Components

<https://nz.rs-online.com>

Element 14

<http://nz.element14.com>

DigiKey

<https://www.digikey.co.nz>



Mouser

<https://nz.mouser.com>

Jameco

<https://www.jameco.com>

Futerlec

<https://www.futurlec.com>

Arrow

<https://www.arrow.com>

UT Source

<https://www.utsource.net>

Donberg

<https://www.donberg.ie>

## Vintage

davenjan2000

<https://www.ebay.com/usr/davenjan2000>

Surplus Electronics

<http://www.surplus-electronics-sales.com>

Small Bear

<http://www.smallbear-electronics.mybigcommerce.com>

Portabellabz

<http://www.portabellabz.be>

Vintage Synth Parts

<http://www.vintagesynthparts.com>

Syntaur

<https://www.syntaur.com/index.php>

Flat Keys

<http://www.flatkeys.co.uk/Dividers/MM5823N.html>

Synth Chaser

<http://synthchaser.com>



## Appendix 8

### Parts Suppliers – Component Price & Shipping Cost Comparison

Jaycar	SI comp	Surplustronik	Global PC	RS	Element14	carzx™	Jameco	Futerlec	DigiKey	WES	Arrow	UT source	Donberg
	\$2.15+		\$1.90	\$1.27+	\$0.73		\$0.39US	\$0.22US	\$0.58	\$0.95A	\$0.40US		
\$2.15	\$1.38+		\$1.60				\$0.45US (10)	\$0.30US	\$1.48	\$1.77A	\$0.53US		
\$2.40	\$2.17+		\$3.10				\$0.55US	\$0.22US	\$0.80	\$0.82A	\$0.52US		
	\$3.64+		\$4.54		\$4.09+		\$1.95US	\$1.10US	\$4.16		\$2.40US		
\$2.65	\$2.48+			\$1.48+	\$1.11+		\$0.49US	\$0.32US	\$0.83	\$1.14A	\$0.53US	Y	
	\$1.82+		\$2.60	\$1.20+	\$1.15+		\$0.69US	\$0.40US	\$1.20	\$1.50A	\$0.71US	\$2.15US	
	\$3.25+			\$1.57+	\$1.31+		\$0.79US	\$0.85US	\$1.19	\$2.14A	\$0.77US		
							\$3.95US	\$1.90US				\$1.30US (10)	5.9eu
	\$1.98+			\$0.32+ (10)	\$0.33+		\$0.08US (10)	\$0.06US	\$0.30	\$0.36A	\$0.13US		
	\$0.72+			\$0.30+ (10)	\$0.39+		\$0.12US (10)	\$0.10US	\$0.30	\$0.25A	\$0.15US		
								\$0.15US	\$1.02		\$0.51US		
												Y	
					\$1.00+		\$0.35US (10)	\$0.60US	\$0.91		\$0.37US		
	\$5.39+			\$1.15+ (5)	\$1.00+		\$0.49US	\$0.45US	\$1.05	\$0.81A	\$0.54US		
													13eu
	\$7.65+						\$1.95US	\$0.95US				\$1US	
	\$1.09+						\$0.55US				\$0.90		
\$1.85								\$0.20US		\$0.47A			1.09eu
\$5.30	\$1.40+	\$1.25	\$1.64		\$2.03+		\$1.79US	\$0.45US			\$1.89US		
					\$2.42+		\$1.19US	\$0.75US			\$2.56US		
\$2.15	\$1.22+				\$3.25+		\$1.89US	\$0.55US			\$2.03US		
\$2.40					\$3.17+		\$1.59US	\$0.85US	\$5.00	\$1.14A			
\$1.65			\$1.15		\$0.87+		\$0.45US	\$0.25US					0.69eu
\$1.40				\$0.81+ (10)	\$0.86+	\$0.55	\$0.45US	\$0.25US	\$0.82	\$0.47A	\$0.45US		0.89eu
\$2.40							\$0.55US	\$0.45US		\$1.14A			1.13eu
\$2.15			\$1.75		\$0.93+	\$0.55	\$0.45US	\$0.50US		\$0.95A			0.89eu
\$1.40		\$1.20	\$1.25		\$0.87+	\$2.20	\$0.45US	\$0.30US		\$0.81A			0.38eu
\$1.40		\$1.20			\$0.93+		\$0.49US	\$0.40US		\$1.00A		Y	0.89eu
							\$2.95US	\$1.10US		\$3.59A		\$0.32US (5)	
\$2.80			\$1.95					\$0.55US					
\$0.43	\$0.74+	\$0.26	\$0.40		\$0.21+ (10)		\$0.14US	\$0.04US	\$0.28+	\$0.07A			
\$0.45	\$0.28+	\$0.33	\$0.40		\$0.22+ (10)		\$0.14US	\$0.06US	\$0.28+	\$0.08A			
\$0.49	\$0.61+	\$0.42	\$0.50					\$0.07US		\$0.10A			
\$1.75	\$1.64+		\$1.25										
			\$1.50										
\$1.75													
\$2.40	\$1.02+		\$1.95	\$0.33 (25)	\$0.85+		\$0.45US	\$0.45US		\$1.09A			
			\$6										
Jaycar	SI comp	Surplustronik	Global PC	RS	Element14	carzx™	Jameco	Futerlec	DigiKey	WES	Arrow	UT source	Donberg
-	-	\$5	-	free	\$16	\$3	\$17US	\$5 to \$7	\$26	?	\$38US	\$2 to \$4US	10eu
					free > \$66		min \$10US		free > \$66			free > \$49US	min 20eu



		icbreakout.com	www.surplus-electronics-	Mouser		Syntaur	
		davenjan2000(ebay)	small bear	Vintage Synth Parts			
<b>Op Amps</b>	pins						
LM358N	8			\$0.50US			
MC1458CP-1	8			\$0.60US			
741	8			\$0.65US			
3130	8			\$2.10US			
726	metal can						
LF353	8			\$0.65US			
CA3094	8			\$8.35US			
TL082	8						
LF356N	8			\$0.60US			
LM3080AN	8		\$2.99US	\$4.95US			
<b>xistors</b>	sub						
2N3904			\$0.45US (5)				
2N3906			\$0.10US				
2N3392				\$0.92			
D16P1							
TIP30							
TIP41							
MPSU05					9.95eu		
<b>TTL</b>							
7413	14						
7426	14	\$8.99US (10)	\$0.40US				
7401	14						
7473	14						
74148	16				\$2.58		
7475	16						
7447	16						
<b>CMOS</b>							
MM5823	14						
4007	14			\$0.45US			
4011	14		\$0.25US	\$0.55US			
4046	16			\$0.75US			
4051BE	16						
4016AE	14						
4051AE	16						
4052B	16						
<b>MISC</b>							
CA3046	14			\$2.25US			
723	14						
MK50240P							
MAN6630	LED disp						
Polycom V DM7670							
Polycom II DM8670							
<b>EXTRAS</b>							
IC socket 8 pin			\$0.10US				
IC socket 14 pin			\$0.10US				
IC socket 16 pin			\$0.12US				
breakout 14 pin	\$US4.25						
header pin 40 way							
90° header pin 40 way							
74LS14							
4520							
DIP veroboard 110x140mm							
		davenjan2000(ebay)	small bear	Mouser			
		icbreakout.com	www.surplus-electronics-sales.com				
		\$US12.59	\$US11.50	\$US14.59	\$US16.25	\$26	
						free >\$66	



## Appendix 9

### IC Manufacturer Prefixes

<i>Prefix</i>	<i>Manufacturer</i>
AD	Analog Devices
Am	Advanced Microdevices (AMD)
CA, CD	RCA
DM	National Semiconductor
H	Harris
HA	Hitachi
I	Intel
ICL, ICM	Intersil
IDT	Integrated Device Technology
L, LD	Siliconix
LF, LH, LM	National Semiconductor
LT	Linear Technology
MC, MM	Motorola
N, NE, SE	Signetics
PM	Precision Monolithics
SN, TL	Texas Instruments
SP	Plessey
WD	Western Digital
XR	Exar
μA	Fairchild Semiconductor

A more comprehensive list can be found here:

<http://www.dialec.com/semiconductorprefixes.html>



## Appendix 10

### Test Equipment Used

Fluke 77 multimeter

Comment: for calibration purposes a DC voltmeter with an accuracy of  $\pm 1\text{mV}$  is required.

Trio 40MHz triple trace delay oscilloscope

Comment: minimum requirement would be a dual trace 20Mhz oscilloscope. A mixed signal oscilloscope will remove the need for a Logic Probe (or Logic Analyser).

Peak LCR meter

Comment: several precision components are used in the PolyMoog. An accurate LCR bridge is required.

STC Logic Probe

Comment: a probe with both TTL and CMOS capability is required. A Pulse capture function is desirable.

HP 5300B Frequency Counter

Comment: an accurate frequency counter is required to set the tuning to  $A = 440\text{ Hz}$



## Appendix 11

### Synthesis Circuit Topologies used in the 1970s

The electronic circuitry available in the 1970s led to engineers using some innovative building blocks in analogue synthesiser design. Some of these are particular to synthesis, whereas others were taken from other fields (eg radio in the case of the PLL's and the MC1495 four-quadrant multiplier).

#### 1. The CMOS Analogue Switch

The CD4016 quad bilateral switch was used extensively to replace individual JFET's for the purpose of switching audio signal paths. Here, the term bilateral indicates that each electronic switch (a SPST configuration) is non-polar. The internal circuitry to achieve this function is an N-channel MOSFET in parallel with a P-channel MOSFET.

A use of the CD4016 is shown in fig. 1. IC3A and IC3D are configured as a partial DPDT switch. IC3B acts as an inverter so that when IC3A is on, IC3D is off (and vice versa). The CD4016 is also used in the TR board to select attack settings, and PWM and FM amount for various presets.

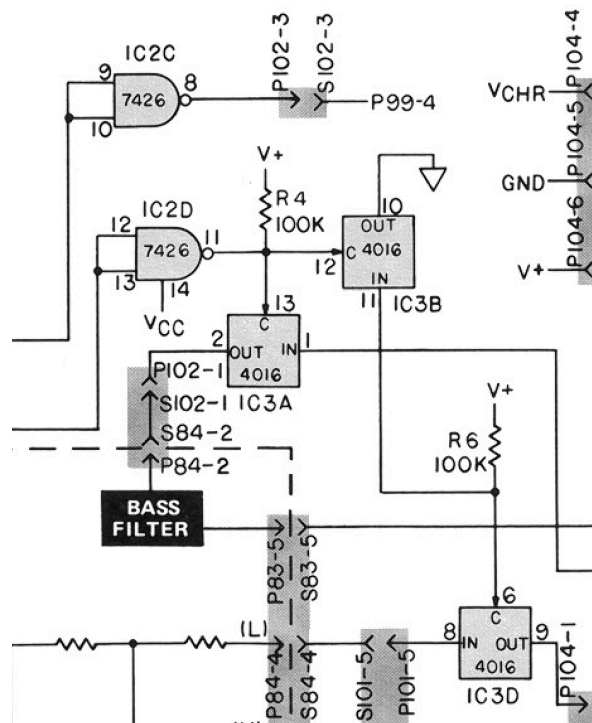


fig. 1. The bass filter select circuit. Source: Moog Music.



When used to switch op amp inputs, care is needed to ensure that the on resistance ( $R_{ON}$ ) does not affect the gain. For this reason, it is preferable to use a non-inverting op amp configuration to avoid variations in the input resistance. Ideally, the switch should be followed by a unity gain buffer. If an inverting op amp is required, large resistor values should be used to minimise the effect.

A later pin-compatible version (the CD4066) superseded it with better specifications (a lower and more consistent on-state resistance). As well as switching, high frequency pulsing techniques were used, for example in the ETI / Maplin synthesizer oscillator. The analogue switch specified is the rare CD4416. All three types exhibit the same basic characteristics. However, care should be taken to replace like with like. The CD4016 has a typical  $R_{ON}$  of  $280\Omega$ , whereas modern analogue switches can have  $R_{ON}$  figures of  $< 1\Omega$ . The  $R_{ON}$  ohmic value and linearity are affected by supply voltage (with  $R_{ON}$  reducing with increased voltage), and input voltage.

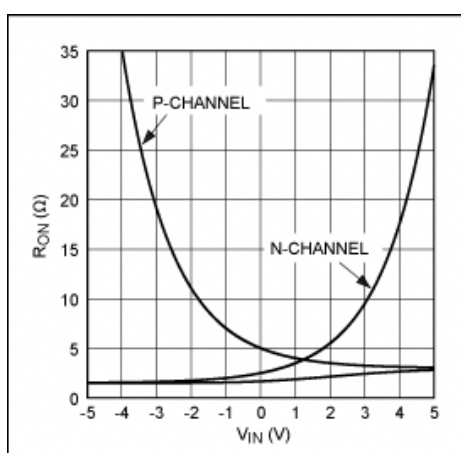


fig. 2.  $R_{ON}$  versus  $V_{IN}$ . Source: Maxim Integrated Application Note 5299

Subtle design differences will affect performance in analogue circuits. The on resistance will be of interest where transistor biasing is involved, and pulsing use will require equivalent dynamic characteristics<sup>32</sup>. A lower  $R_{ON}$  figure will result in increased input capacitance. For S/H applications the CD4016 is recommended.<sup>33</sup> Distortion of the CD4016 is high by today's standards (at 0.5% it is two orders greater than the best performing modern analogue switch).

<sup>32</sup> examples include the ETI synthesizer VCO and VCF circuits

<sup>33</sup> T. I. Datasheet schs051g – November 1998 – revised June 2017



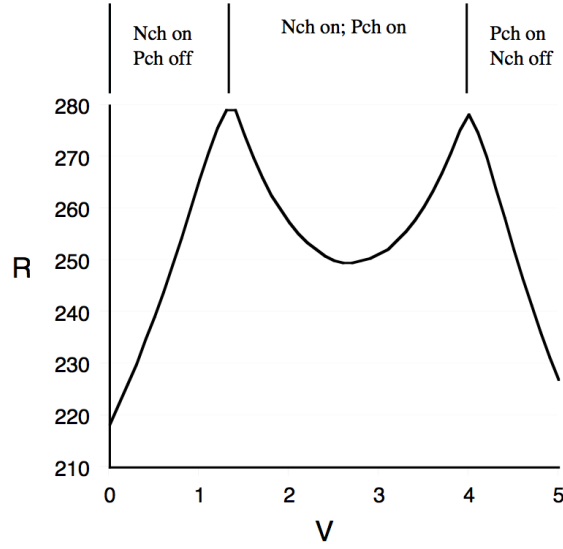


fig. 3. Combined N-channel and P-channel transfer function. Source: Allen and Holberg - CMOS Analog Circuit Design.

## 2. The Phase Locked Loop

The Phase Locked Loop (PLL) is a type of negative feedback control system, with the transfer function:

$$\frac{Y(s)}{X(s)} = \frac{G(s)}{1 + G(s)H(s)}$$

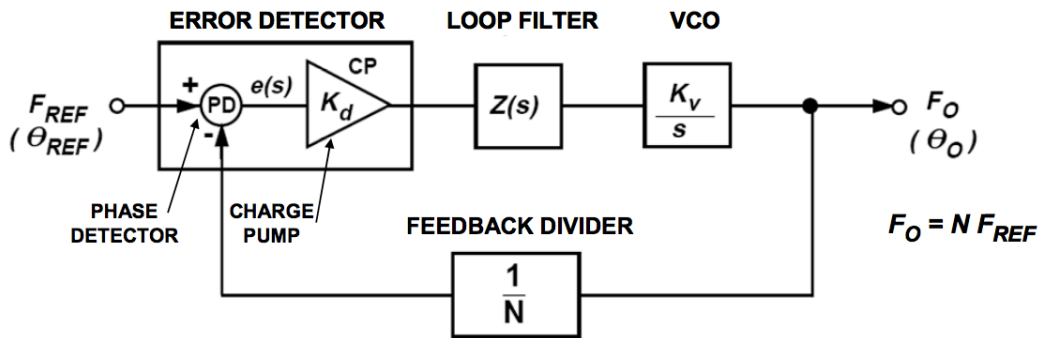


fig. 4. The PLL model. Source: Analogue Devices MT-086.

Referring to figure 4, a HF VCO generates an output at  $F_O$ . This output is also divided by  $N$  and sent to the error detector.  $F_{REF}$  can be a LF reference oscillator that is also an input to the error detector. This element acts as a phase comparator between these two signals generating an output according to the phase difference, which is fed to the VCO. The VCO will change frequency to eliminate any phase difference between it and  $F_{REF}$ . A loop filter is required to band-limit the control signal to ensure system stability.



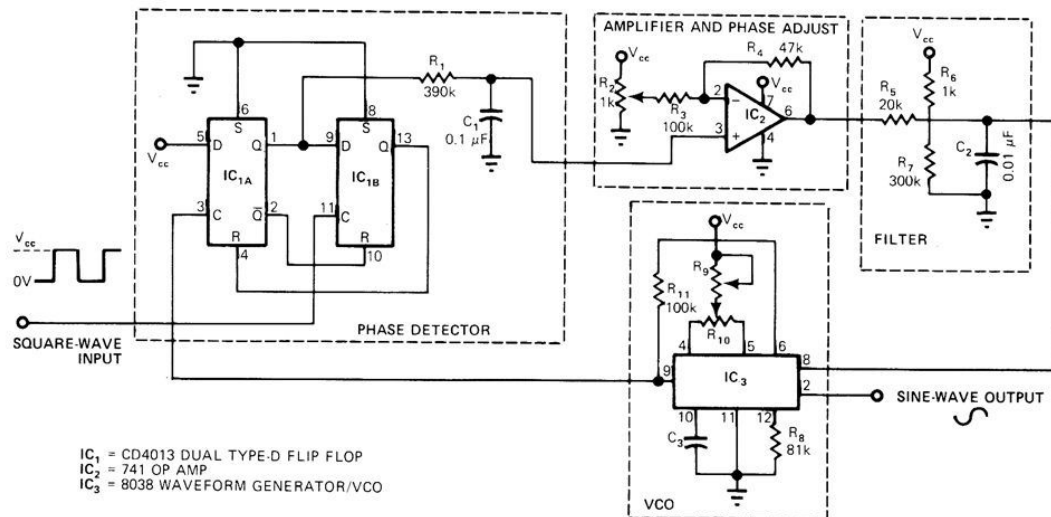


fig. 5. example of a PLL controlling a waveform generator. Source: <http://www.seekic.com>.

### 3. The Ladder Filter

Possibly the most famous of all the analogue synthesizer building blocks, the Moog ladder filter gives a distinctive sound. This is partly due to distortion of the transistors, but the most notable characteristic is that of a LPF that resonates without losing much low frequency content. It was largely responsible for what defined 'the' analogue synthesizer sound.

Such was its success that ARP copied the ladder filter design in their Odyssey synthesizer. Moog issued a lawsuit for this infringement, with the two companies settling out of court.<sup>34</sup> The Roland SH2000 filter also shows an infringement of the Moog patent.

Details of the filter are shown in US patent 3475623.<sup>35</sup> The design was driven by the problem of finding a suitable circuit to produce voltage control for the filter cut-off frequency. Dr Moog came up with a novel solution, which was to use the dynamic resistance of a string of transistor emitter junctions in conjunction with capacitors to vary the filter cut-off;

$$f_c = \frac{rC}{2}$$

Where  $r$  = dynamic resistance of the base-emitter junction pair. Using the exponential transfer relationship of transistors provided a wide operating range (1000:1), so that the full audio spectrum was under voltage control.

Transistors are used in a complimentary pair configuration to provide a balanced circuit that prevents any of the control voltage appearing on the output.

<sup>34</sup> <http://www.vintagesynth.com/arp/odyssey.php>

<sup>35</sup> <https://patents.google.com/patent/US3475623>



Four stages are incorporated into the design to give a slope of 24dB/octave. The transfer function is

$$H(s) = \frac{1}{(s + 1)^4}$$

To make the filter resonate an amount of feedback ( $\beta$ ) is needed:

$$H(s) = \frac{1}{(s + 1)^4 + \beta}$$

Because the cut-off frequency is proportional to an exponential control voltage, musical intervals are proportional to the control voltage. This was another significant advantage of this design.

A detailed analysis of the Moog ladder filter has been completed by Tim Stinchcombe.<sup>36</sup>

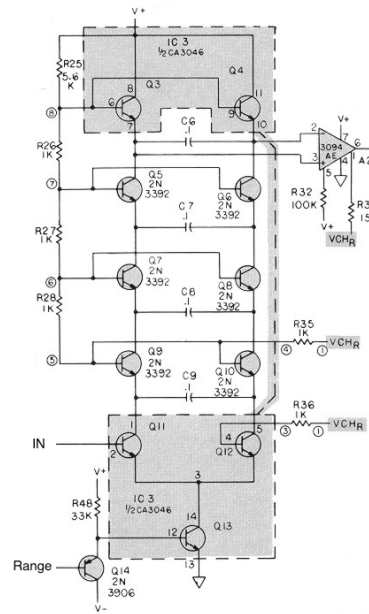


fig. 6. The Ladder Filter, as implemented in the PolyMoog. Note the use of a CA3046 transistor array and discrete transistors. Source: Moog Music.

<sup>36</sup> [http://www.timstinchcombe.co.uk/synth/Moog\\_ladder\\_tf.pdf](http://www.timstinchcombe.co.uk/synth/Moog_ladder_tf.pdf)



#### 4. The Operational Transconductance Amplifier

The Operational Transconductance Amplifier (OTA) forms an important building block for analogue synthesizer circuitry. This due to its ability to act as the control element for a VCA or VCF. Before DSP techniques became common, the OTA had numerous uses (such as multiplexing and modulation) but is now an obsolete component. Consequently, devices such as the CA3080 and CA3094 are becoming difficult to source.

The OTA outputs current proportional to a differential input voltage:

$$g_m = \frac{\delta i_{out}}{\delta v_{in}}$$

where  $g_m$  is transconductance.

Gain is controlled by a separate input current, thus making the OTA a ready-made VCA. The CA3080 exhibits good linearity up to a bias current of 200 $\mu$ A, with a 1:1 ratio of output current to bias current. Roland used the CA3080 in several of its synthesizer filters, before developing its integrated four-OTA IC (the IR3109).

#### 5. The Four Quadrant Multiplier

Another way of achieving control of a VCA or VCF is to use a four-quadrant multiplier. Four Quadrant means that both inputs can be a bipolar signal. A popular choice in the 70s was the MC1495<sup>37</sup> IC. This device produces a linear product of two input voltages, so that when a DC voltage is applied at  $V_C$ , the amount of  $V_{IN}$  presented at  $V_{OUT}$  will be directly proportional to that voltage. A logarithmic converter is required to use the device as a VCA.

---

<sup>37</sup> a similar IC, the MC1496 balanced modulator, was also used



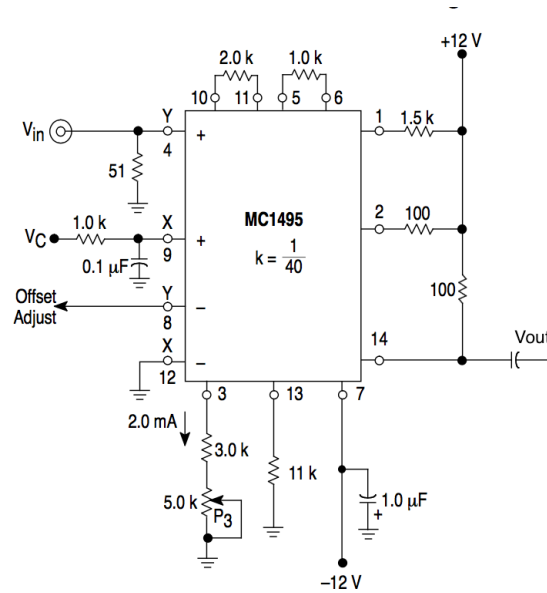


fig. 7. The MC1495 configured as a linear gain control. Source: Motorola

## 6. The Monolithic Transistor Array

These were used to provide thermal stability to oscillator circuits to control tuning drift. IC examples include the  $\mu A726$  and the CA3046. The  $\mu A726$  has a long-term voltage drift of only  $5\mu V$  per week. This is due to the inclusion of oven circuitry to maintain the transistors at a constant temperature. Prior to these ICs being available, temperature compensation techniques included using thermistors or discrete transistors bonded together in an enclosure. These methods were less effective due to mismatches, and the non-linear nature of these devices. Apart from the PolyMoog, the  $\mu A726$  was used in several Roland synthesizers.<sup>38</sup>

VCO circuits will typically take the input voltage and convert it to an exponential current. This function is the natural characteristic of the transistor junction, as defined by the Ebers Moll equation:

$$I_c = I_s [\exp(qV_{be} / kT) - 1] \quad (1)$$

Where  $I_s$  is collector leakage current, and is largely dependent on temperature.

<sup>38</sup> eg SH2, SH5, SH7, Jupiter 4, System 700



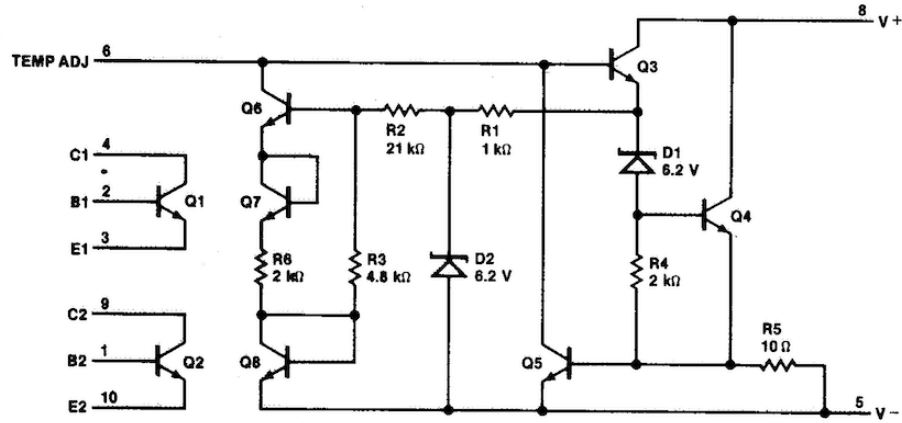


fig. 8. The  $\mu A726$  equivalent circuit. Source: Fairchild Semiconductor.

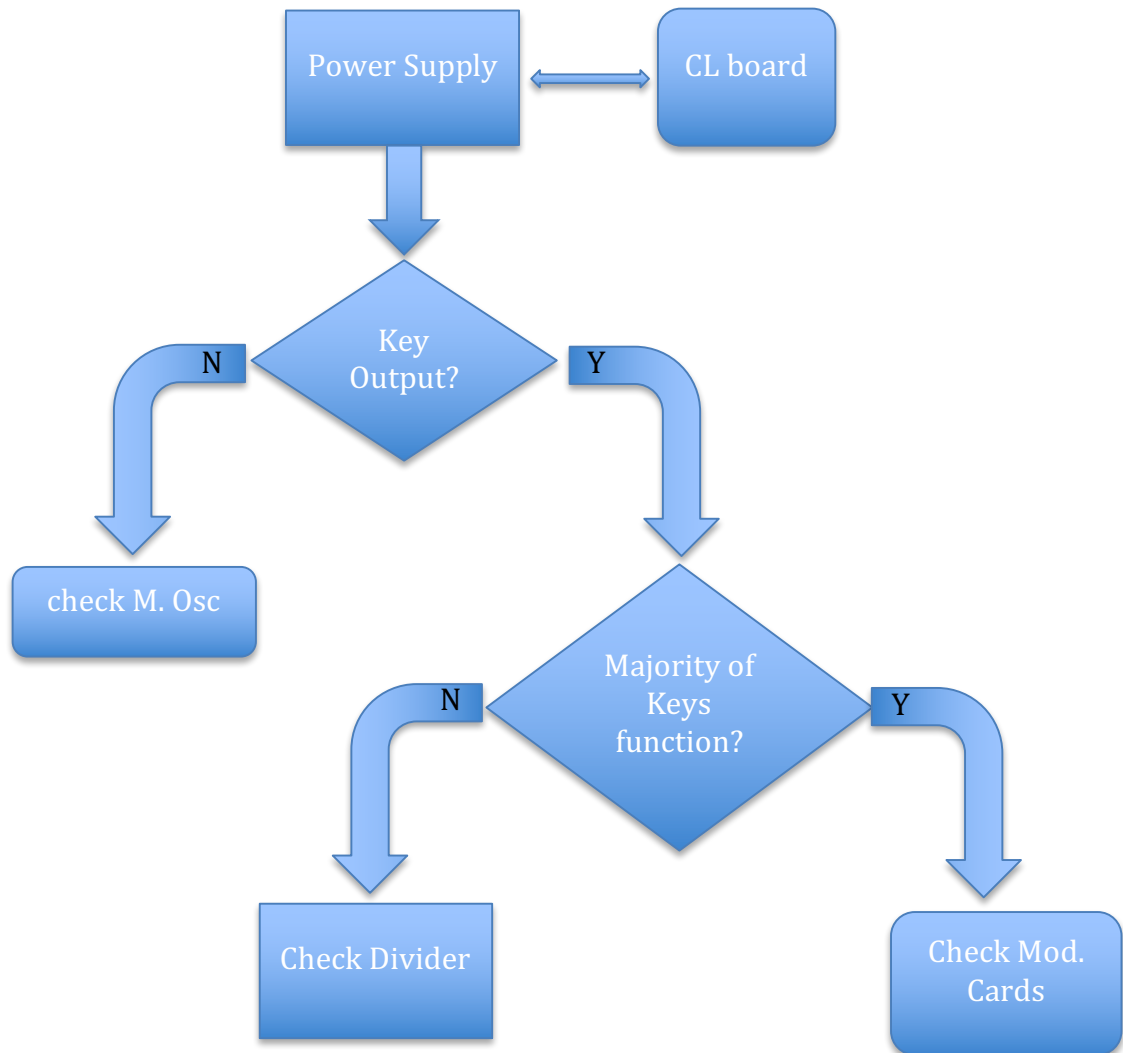
by rearranging (1) we get  $\partial V_{be} = (kT/q) \ln(I_{CQ2}/I_{CQ1})$  (2)

This is the usual case of a differential pair used, where the second transistor provides temperature compensation. By providing a current mirror with a reference current source the effects of  $I_s$  can be cancelled.

By using the  $\mu A726$  in both of the reference oscillator circuits, short-term pitch stability of 0.02% ( $\pm 1/3$  Cent) was obtained in the PolyMoog.



Appendix 12  
Repair Assessment Chart





## Appendix 13

### The PolyPedal

A discussion of the PolyMoog sound and performance capabilities is incomplete without mention of the PolyPedal. This rather large unit provides control of features that are otherwise lacking. Moog decided which effects and controls would function on the presets according to the norms of the instruments that are being emulated<sup>39</sup>.

The PolyPedal changes the PolyMoog Keyboard into a versatile performance instrument. When the PolyPedal is employed the range of synthesis tones is greatly improved. This aspect of design reveals the Moog philosophy: that creating intriguing sounds was only part of the design; just as important was that the synthesizer should be a playable musical instrument with a good user interface.

The controls are as follows:

Swell: this is a volume pedal, and is particularly suited for Rock Organ

Sustain: this activates the envelope sustain. The sustain length is determined by the preset selected.

Left pedal: this can be assigned to pitch and/or filter sweep by the use of two foot switches. The filter cutoff frequency is only controllable on the Brass presets. The pitch shift is a powerful effect as it sweeps frequency polyphonically. A range adjustment allows the ascending sweep to be set anywhere up to 1 octave. This is much more useful than the ribbon controller that has a range of  $\pm$  major 6<sup>th</sup>.

Trigger Mode: when depressed this pedal changes the trigger mode between single and multiple. A switch at the rear of the PolyPedal changes the off state to either mode. The usefulness of this control cannot be overstated. Dave Luce was a brilliant electronics engineer, but it was Bob Moog who oversaw the controller aspects of the design. Providing a piano style pedal for trigger mode indicates how much thought was put into the PolyMoog being an expressive performance instrument. Both single and multiple triggering of the filter are useful, and this pedal greatly enhances the polyphonic playability.

### Modulation Depth Modification

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<sup>39</sup> see appendix 13



Scott Juskiw<sup>40</sup> has published a modification to the PolyPedal that reuses the Pitch pedal as a Modulation Depth control. With the addition of a suitable switch it should also be possible to select either option.



*fig. 1. A Cinch Jones power connector is used on the PolyPedal. Source: <https://www.vintagevibe.com>*

## Appendix 14

### Parameter Setting for the Presets

Modulation parameters for the 14 presets are listed in Table 6-3 of the PolyMoog service manual.

The modulation amount effects the PWM only on the Strings and Rock Organ presets. FM is active from osc 1 and osc 2 only on the Strings presets. Otherwise it is from one FM osc only, with the exception being that there is no FM on the Rock Organ preset.

The modulation rate is fully pre-set for the Strings presets, and for PWM for the Clav preset. PWM rate is only variable on the Rock Organ preset. The other presets have either FM osc 1 or osc 2 with variable rate.

The Beat control is only active on these presets: Vox Humana, Strings, and Honky Tonk Piano.

Attack is pre-set for all the percussive keys, Rock Organ, and Funk presets.

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<sup>40</sup> <http://tellun.com/polymoog/polymoog.html>



## Appendix 15

### Synthesizer Terminology

#### Monophonic

Only a single note can sound at a time.

#### Duophonic

Two notes can sound simultaneously.

#### Polyphonic

More than two notes can sound simultaneously.

#### Paraphonic

All notes can sound simultaneously, but through a shared voice.

#### x-Note (eg 8 note)

The maximum number of notes that can sound simultaneously.

#### x-Voice (eg 8 voice)

The maximum number of generator/articulation channels. This is sometimes expressed as voices per note.

#### Note Priority

The priority of notes played. For a monophonic synthesizer, this means what note overrides the previous note played. The order can be Low Note Priority, High Note Priority, or Last Note Priority (desirable). First Note priority is where the first key must be released before a second note will sound (undesirable).



## Control Voltage (CV)

The voltage sent to the voltage control modules (eg VCO, VCF, VCA).

For controlling a VCO there are two standards:

### Volts per Octave (linear)

- each volt = 1 octave, eg 2v = A2, 3v = A3, 4v = A4
- used by Moog, Arp, Oberheim, Sequential Circuits, Roland, and most modern synthesizers

### Hertz per Volt (exponential)

- one octave = double (or half) the voltage, eg 2v = A2, 4v = A3, 8v = A4
- used by Korg, Yamaha

## Gate

A signal that is sent from the keyboard when a key is played to start an Envelope Generator. The signal state change will be held as long as the key is depressed.

## Trigger

A transient signal that is sent from the keyboard when a key is played to start an Envelope Generator.

## Single Triggering

The Envelope Generator will trigger on the first note played, but not on subsequent notes, until all the keys are released (on a Polyphonic Synthesizer).

## Multiple Triggering

The Envelope Generator will trigger on the first note played, and on subsequent notes played (on a Polyphonic Synthesizer).



## Appendix 16

### Polyphonic Synthesizers of the 1970s – early 80s

Model	Year Intro.	Polyphony	Price
ARP Odyssey	1972	2 voice	
Moog Sonic Six	1972	2 voice	
Buchla 237	1970s	3 voice	
Buchla 238	1970s	4 voice	
E-mu Modular System	1972	2 voice	
Moog Apollo	1973	61 voice	
Yamaha GX1	1975	2 x 8 voice	\$60,000
Oberheim 2 Voice	1975	2 voice	
Oberheim 4 Voice	1975	4 voice	
Moog PolyMoog 203A	1975	71 voice	
ARP Omni	1975	49 voice	
Korg PE-1000	1976	60 voice	
Yamaha CS-80	1976	8 voice	\$6900
Korg PS-3300	1977	48 note	
SC Prophet V	1978	5 voice	\$4595
Roland Jupiter 4	1978	4 voice	\$2895
Oberheim OB-X	1979	4, 6 and 8 voice	\$4595 (4 voice)
Memory Moog	1982	6 voice	
Yamaha DX7	1983	16 voice	