MSK 013 Middle Path Voltage-Controlled Oscillator

North Coast Synthesis Ltd.
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September 14, 2021

Contents

General notes

This manual documents the MSK 013 Middle Path Voltage-Controlled Oscillator, which is a module for use in a Eurorack modular synthesizer. The module contains two triangle-core oscillators and a shaping circuit based on the Gilbert sine shaper modified for quadrature output. The oscillators can be used independently as V/oct synthesizer oscillators, or synchronized to produce more complex timbres. The sine shaper can be used to achieve through-zero phase modulation effects even though the oscillator cores themselves do not operate through zero.

Oscillator controls and connections

The front panel of the Middle Path VCO is shown in Figure 1. The two oscillator sections, which are called oscillator A or the *master* on the left and oscillator B or the *slave* on the right, have the same controls and connections in mirror image and to within engineering tolerances they should operate identically when used by themselves. They differ in their normalizations and in the way they interact with the sync circuit.

Tuning knobs, coarse and fine These knobs set the base frequency of the oscillator, which can be modified by applying V/oct pitch and FM input voltages. The coarse knob covers a range of approximately ten octaves and the fine knob approximately half an octave. The oscillator is designed to cover the entire audible spectrum, and these knobs correspond to that range (approximately 20Hz to 20kHz) when the input pitch and FM voltages are zero.

V/oct pitch input This input controls the oscillator's frequency according to the usual Eurorack exponential 1.0V/octave scheme. See the notes below regarding normalization of this input.

It is not possible to push the oscillator much above the high end of the audio range. With significant positive control voltage, the frequency will go as high as it can when the coarse tuning is somewhere below maximum, and then turning the knob further (or increasing the voltage) will not drive the frequency any higher. On the other hand, with negative control voltage it should be possible to drive the oscillator well into the sub-audio LFO range, but it may not track accurately below audio frequencies, and at very low frequencies the triangle wave will become asymmetrical and eventually flatten out. On my first prototype, the upper and lower limits for well-behaved oscillation were about 27kHz and three minutes per cycle respectively. These limits would be expected to vary a little with individual modules.

FM knob and input The FM input is an additional exponential pitch control voltage input, with attenuation controlled by a knob. When the knob is turned fully clockwise, the sensitivity of this input is nominally 1.0V/oct, though not as accurately so as the main V/oct input. With the knob at other settings, the sensitivity of the FM input will be less.

PWM knob and input The PWM input and its associated knob control the pulse width of the PULS output. The input control voltage from the jack socket is attenuated by the knob and then applied to one input of a comparator, with the oscillator TRI output applied to the other input. The jack socket is normalized to the equivalent of a little over 5V.

A control voltage patched into the jack socket directly controls the duty cycle of the PULS output. The comparator used to generate the pulses is inverting, so the nominal range of duty cycles for control voltage ranging from -5V to +5V is from 100% down to 0% duty cycle, when the attenuator is turned fully clockwise. At other settings, the modulation will be less sensitive, and centred on 0V = 50%.

Without a cable patched in, the PWM knob directly controls duty cycle from 50% at full counterclockwise down to a little past 0% at full clockwise. This control range is designed to make finding the 50% point, for quadrature effects, as easy as possible; the range goes a little past 0% at the other end to make sure it will be possible to turn the knob all the way to 0% even in the face of small variations in oscillator amplitude.

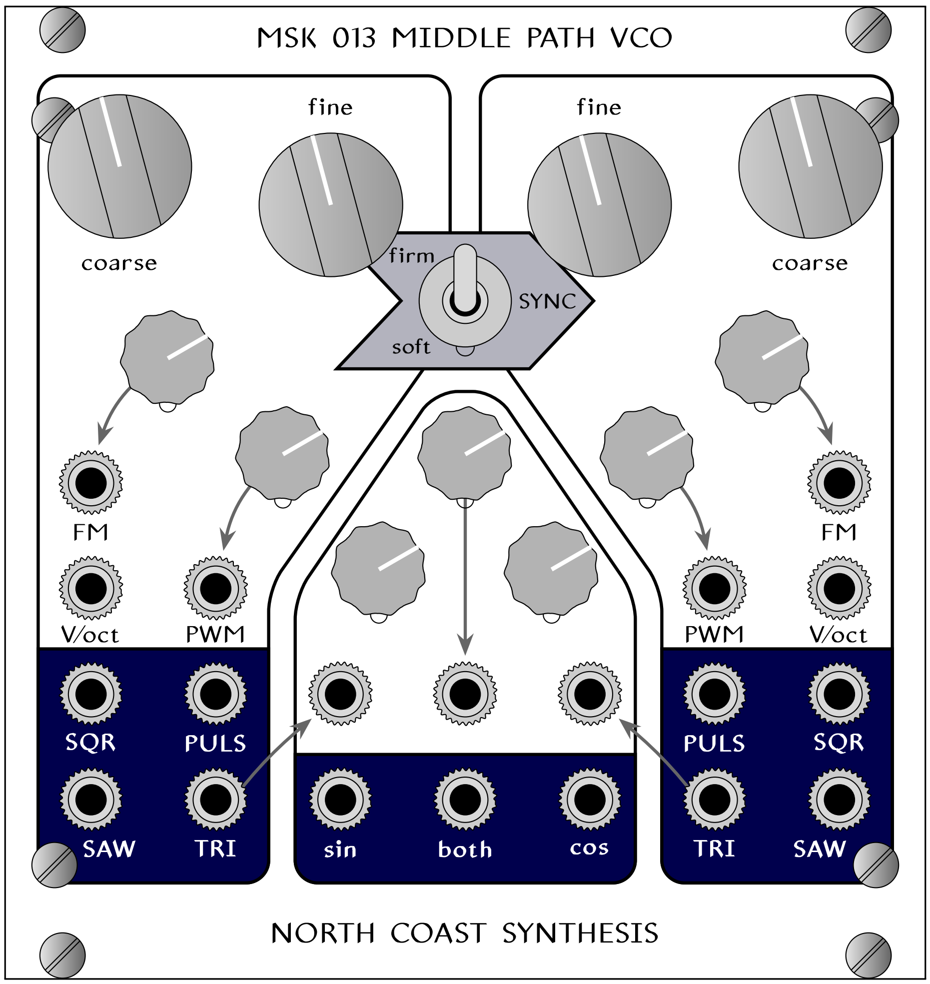


Figure 1: Module front panel.

TRI output This is the main output from the oscillator core: a triangle wave of nominally 10V peak to peak (±5V).

SQR output This square output also comes from the oscillator core, so it should be quite accurately 50% duty cycle and always synchronized with the TRI output: +5V when TRI is going up, and −5V when TRI is going down.

PULS output The PULS output is a variable-width nominal ±5V pulse derived from the TRI signal and the pulse width modulation system. With the PWM knob turned fully counterclockwise, or zero PWM control voltage, the PULS output will have 50% duty cycle, but because it derives from a comparator on the TRI signal instead of directly from the core, the PULS output will be in quadrature (90° phase difference) with the SQR output.

Because the duty cycle changes with pulse width modulation and the high and low voltages do not, this output will have an average voltage of 0V only when the duty cycle is 50%. At other duty cycles, it will have a non-zero average voltage, or "DC offset" by some definitions.

SAW output The SAW output is a rising sawtooth wave of nominally 10V peak to peak (±5V) derived by waveshaping from the TRI and SQR signals.

Quadrature sine shaper

The Middle Path VCO's quadrature sine shaper combines oscillator outputs, or external inputs, to create a variety of different spectral effects. It is a variation of the sine shaper disclosed by Barrie Gilbert in US Patent #4,475,169A modified to produce three outputs including a quadrature pair. Depending on the settings and input, this section can shape an oscillator output into a simple sine wave or two in quadrature; do through-zero phase modulation, which is identical to frequency modulation in the case of a sine-wave modulation input; or create a range of distortion, wavefolding, and imitation stereo effects.

Input to the shaper comes through a three-input mixer. Then the result of mixing is applied to the shaper proper, which computes three sine-like functions of the mixed voltage. Figure 2 shows idealized versions of these functions; exact voltage values on both axes will vary a little with component tolerances. There are three input jacks which can receive patch cables; if left unpatched, the left and right input jacks are normalized to receive the TRI outputs of the two oscillators, and the centre jack receives a normalized DC voltage equivalent to an external input of about +4.5V. Each input jack has its own knob controlling its contribution to the mix.

It is difficult to concisely describe or predict what the shaper will audibly do to signals, and in musical practice it's probably best to just adjust it by ear, playing with the levels until the output sounds good. In brief: input signals get mixed together and distorted. There's more distortion, shifting to higher harmonics, as the signal levels increase; and more on the "both" output than on the "sin" and "cos" outputs. Two or more signals will modulate each other. Knowing those basics should be enough to get sound out of it. But there are some additional notes on what's really going on from a mathematical and electronic point of view, in the circuit explanation and sample patch chapters later in this manual.

The simplest way to use the shaper is to leave the inputs unpatched, on their normalized signals. With just one oscillator input knob turned up, the outputs will be the triangle outputs of the corresponding oscillator with more or less distortion. At very low levels the triangle comes through in its original shape, just attenuated. At higher levels, the "both" output will approach a sine wave; past that point, the peaks of the sine wave will start to fold back, creating even-harmonic distortion of the kind sometimes associated with vacuum tubes. At even higher levels, the distortion turns into full wave-folding as the spectrum shifts to higher and higher harmonics.

With both oscillator inputs turned up, harmonics of both show up in the output, but also intermodulation products between them. If one oscillator is at a much lower frequency then the other, the higher-frequency oscillator is effectively the carrier and the lower-frequency one is the modulator, in a through-zero phase modulation effect. In the default patching this is triangle phase modulation of a triangle wave, which produces a somewhat broader spectrum than the original Chowning-type sine-modulating-sine through-zero effect.

To create a true sine-wave carrier, patch the carrier oscillator's sawtooth output into the shaper instead of using the triangle normalization, and then adjust the carrier level to get as pure a sine wave as possible before applying modulation either from an external signal or the other oscillator. This will be a low level for the carrier input; the modulator signal would usually be a lower frequency and higher level, in order to drive the carrier backwards and achieve through-zero. To achieve a true sine wave for the modulator as well would require using an external sine wave as input, but the normalized triangle wave is spectrally very close.

The "sin" and "cos" outputs are 90° apart in the voltage/voltage function, but exactly what that means in terms of the sound may be complicated. It's interesting to treat them as "left" and "right" stereo channels; listeners' ears will pick up the phase differences as different physical locations for different spectral components. These two signals can also be considered as two less-distorted (lower modulation index) versions of what comes out of the "both" output.

To get two true sine waves 90° apart from the quadrature shaper, patch an oscillator's *sawtooth* output into the shaper instead of using the normalization, and then adjust the level to make the sine waves spectrally pure. In this case the "both" output will also produce a sine wave, at twice the frequency. All three outputs will have small glitches created by the sawtooth's reset time, but these should be at sufficiently high ultrasonic frequencies not to present a problem.

Note that the outputs of the sine shaper may go to about ±8V if it is driven beyond the range of its sine functions. Under those conditions the theoretical ideal of its spectral behaviour will break down and the distortion will become significantly harsher. At input levels within the sine-wave region, its output should be similar to levels of the oscillator outputs, around ±5V or maybe as much as ±5.5V.

Sync mode

The SYNC toggle switch has three positions: "soft," "firm," and an unlabelled off position in the middle. With sync turned off, the two oscillator cores function independently. But in either of the other two modes, pulses from the master core are used to modify the operation of the slave core. Sync forces the slave's output spectrum to be harmonically related to the master frequency, but with the details of the spectrum defined by the free-running frequency of the slave. It's a popular feature for constructing complex musical timbres.

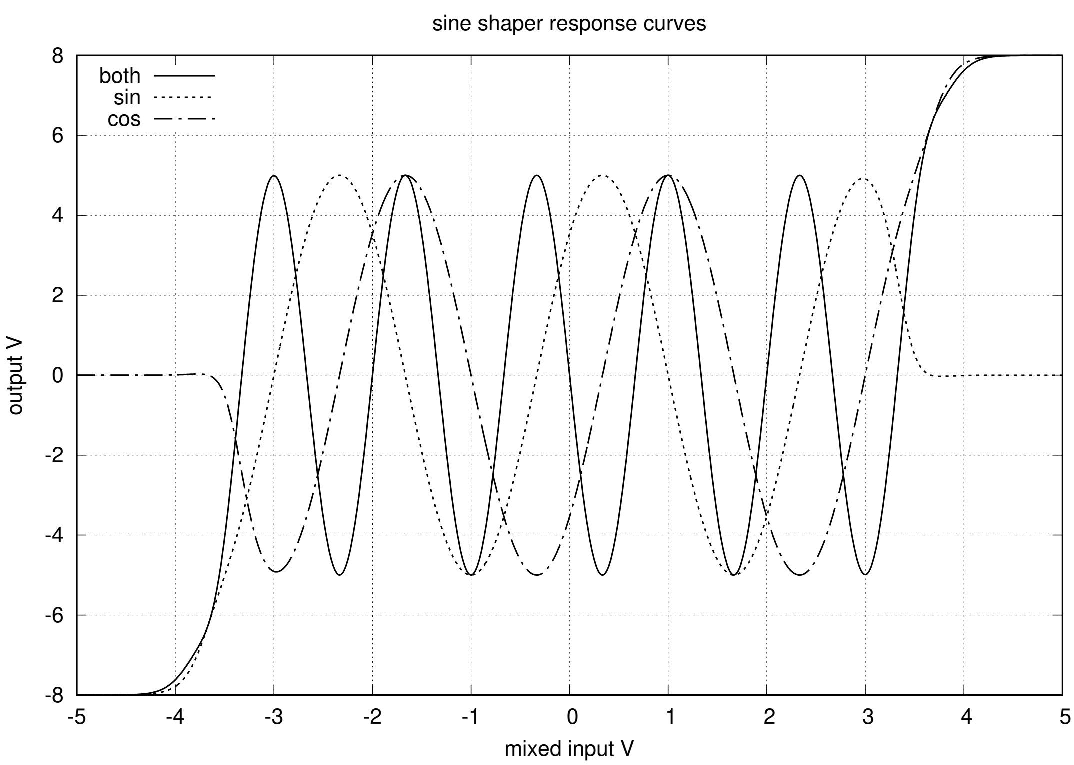


Figure 2: Quadrature sine shaper voltage functions.

In “soft” mode, the slave oscillator is forced into the rising direction on every rising edge of the master’s SQR output, which corresponds to the lowest point in the master triangle waveform. This form of sync will eventually force the slave to force to a multiple or submultiple of the master frequency, but it may take a perceptible time to lock.

In “firm” mode, the slave oscillator is forced to the same direction as the master on every edge, in either direction, of the master’s PULS output. That means the exact effect of firm sync will vary depending on the pulse width and PWM of the master oscillator. This mode usually creates a tighter lock, with the slave moving to match the master faster when the frequency changes.

Sync pulses are applied directly to the Schmitt trigger in the slave’s core, which is also the source of the slave’s SQR output; and there is a refractory period after each sync pulse during which the slave’s normal direction-switching will not function. As a result, both the SQR and TRI outputs of the slave may go outside their usual voltage range when sync is activated. DC offset may also show up at some settings; for instance, with master frequency significantly higher than slave frequency, the slave’s triangle output will be forced to stay near its upper limit most of the time.

Specifications

The nominal input impedance is at least 100kΩ for all inputs. When inputs are normalized together, they appear in parallel – so, for instance, the master pitch CV will have 50kΩ impedance if it also drives the slave through the standard normalization. Nominal output impedance is at most 1kΩ for all outputs.

Any voltage between the power supply rails (nominally ±12V) is safe for the module, on any input; output voltages are limited by the capabilities of the op amps to about ±10V and will clip if the inputs are driven sufficiently hard. The nominal output voltage range for all outputs, and expected range for all inputs in normal use, is nominally ±5V. The exact maximum and minimum output voltages may vary but will often be slightly wider, such as ±5.5V.

Briefly shorting any output to any fixed voltage at or between the power rails, or shorting two to each other, should be harmless to the module. Note that “between the power rails” does mean it is safer to feed voltages into the module when power is applied, since without power, both power rails will be at zero. Patching the MSK 013’s output into the output of another module should be harmless to the MSK 013, but doing that is not recommended because it is possible the other module may be harmed.

This module contains series reverse protection diodes and is unlikely to be damaged by a reverse power connection, but because it uses a 16-pin power connection there are more kinds of misconnection possible than pure reversal of the main power rails. It is possible that there could be a short circuit, more likely damaging to the power supply than to the module, if the power is misconnected. The connector on the module is polarized and unlikely to be misconnected, but some caution is still recommended when connecting the cable at the bus board.

The maximum current demand of this module in normal operation is 75mA from the +12V supply and 105mA from the -12V supply. Placing an unusually heavy load on the outputs (for instance, with so-called passive modules or output-to-output patching) can increase the power supply current beyond those levels.

Source package

A ZIP archive containing source code for this document and for the module itself, including things like machine-readable CAD files, is available from the Web site at https://northcoastsynthesis.com/. Be aware that actually building from source requires some manual steps; Makefiles for GNU Make are provided, but you may need to manually generate PDFs from the CAD files for inclusion in the document, make Gerbers from the PCB design, manually edit the .csv bill of materials files if you change the bill of materials, and so on.

Recommended software for use with the source code includes:

- GNU Make;
- LaTeX for document compilation;
- LaTeX.mk (Danjean and Legrand, not to be confused with other similarly-named LaTeX-automation tools);
- Circuit_macros (for in-document schematic diagrams);
- Kicad (electronic design automation);
- Qcad (2D drafting); and
- Perl (for the BOM-generating script).

The kicad-symbols/ subdirectory contains my customised schematic symbol and PCB footprint libraries for Kicad. Kicad doesn’t normally keep dependencies like symbols inside a project directory, so on my system, these files actually live in a central directory shared by many projects. As a result, upon unpacking the ZIP file you may need to do some reconfiguration of the library paths stored inside the project files, in order to allow the symbols and footprints to be found. Also, this directory will probably contain some extra bonus symbols and footprints not actually used by this project, because it's a copy of the directory shared with other projects.

The package is covered by the GNU GPL, version 3, a copy of which is included in the file COPYING.

PCBs and physical design

The enclosed PCB design is for two boards, each 4.60″×4.20″ or 116.84mm×106.68mm. The two boards are intended to mount in a stack parallel to the Eurorack panel, held together with M3 machine screws and male-female hex standoff hardware. See Figure 3. Including 12mm of clearance for the power connector and cable, the module should fit in 36mm of depth measured from the back of the front panel.

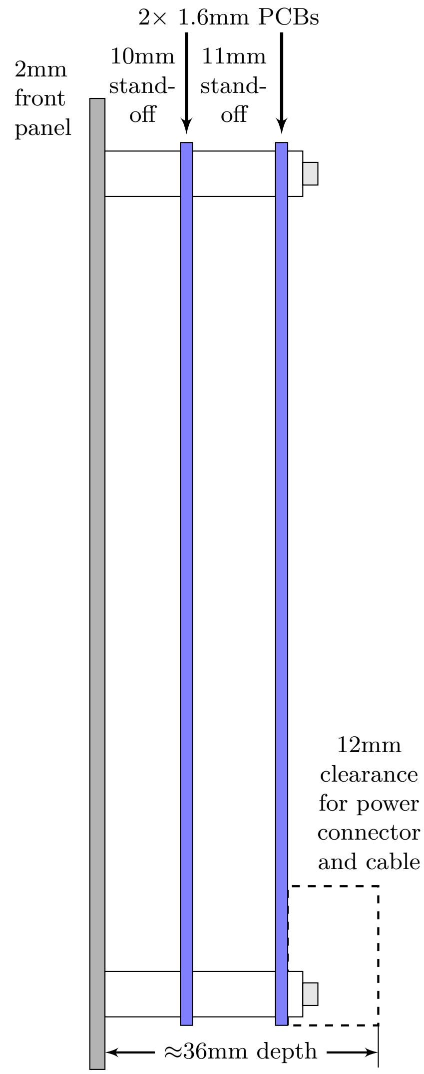


Figure 3: Assembled module, side view.

Use and contact information

This module design is released under the GNU GPL, version 3, a copy of which is in the source code package in the file named `COPYING`. One important consequence of the license is that if you distribute the design to others – for instance, as a built hardware device – then you are obligated to make the source code available to them at no additional charge, including any modifications you may have made to the original design. Source code for a hardware device includes without limitation such things as the machine-readable, human-editable CAD files for the circuit boards and panels. You also are not permitted to limit others' freedoms to redistribute the design and make further modifications of their own.

I sell this and other modules, both as fully assembled products and do-it-yourself kits, from my Web storefront at http://northcoastsynthesis.com/. Your support of my business is what makes it possible for me to continue releasing module designs for free. The latest version of this document and the associated source files can be found at that Web site.

Email should be sent to
mskala@northcoastsynthesis.com.

Safety and other warnings

Ask an adult to help you.

North Coast Synthesis Ltd. does not offer warranties or technical support on anything we did not build and sell. That applies both to modules built by you or others from the kits we sell, and to fully-assembled modules that might be built by others using our plans. Especially note that because we publish detailed plans and we permit third parties to build and sell modules using our plans subject to the relevant license terms, it is reasonable to expect that there will be modules on the new and used markets closely resembling ours but not built and sold by us. We may be able to help in authenticating a module of unknown provenance; contact us if you have questions of this nature.

For new modules purchased through a reseller, warranty and technical support issues should be taken to the reseller *first*. Resellers buy modules from North Coast at a significant discount, allowing them to resell the modules at a profit, and part of the way they earn that is by taking responsibility for supporting their own customers.

We also sell our products to hobbyists who enjoy tinkering with and customizing electronic equipment. Modules like ours, even if originally built by us, may be quite likely to contain third-party "mods," added or deleted features, or otherwise differ from the standard specifications of our assembled modules when new. Be aware of this possibility when you buy a used module.

Soldering irons are very hot.

Solder splashes and cut-off bits of component leads can fly a greater distance and are harder to clean up than you might expect. Spread out some newspapers or similar to catch them, and wear eye protection.

Lead solder is toxic, as are some fluxes used with lead-free solder. Do not eat, drink, smoke, pick your nose, or engage in sexual activity while using solder, and wash your hands when you are done using it.

Solder flux fumes are toxic, *especially* from lead-free solder because of its higher working temperature. Use appropriate ventilation.

Some lead-free solder alloys produce joints that look "cold" (i.e. defective) even when they are correctly made. This effect can be especially distressing to those of us who learned soldering with lead solder and then switched to lead-free. Learn the behaviour of whatever alloy you are using, and then trust your skills.

Water-soluble solder flux must be washed off promptly (within less than an hour of application) because if left in place it will corrode the metal. Solder with water-soluble flux should not be used with stranded wire because it is nearly impossible to remove from between the strands.

Residue from traditional rosin-based solder flux can result in undesired leakage currents that may affect high-impedance circuits. This module does not use any extremely high impedances, but small leakage currents could possibly reduce its accuracy. If your soldering leaves a lot of such residue then it might be advisable to clean that off.

Voltage and current levels in some synthesizer circuits may be dangerous.

Do not attempt to make solder flow through the board and form fillets on both sides of every joint. Some soldering tutorials claim that that is desirable or even mandatory, it does look nicer, and it may happen naturally when the conditions are good and the leads happen to be small in relation to the holes. But with large wire leads that just fit in the holes, when the holes are connected to the ground plane (even through thermal reliefs), on some harder-to-wet lead finishes, with lead-free solder, and so on, you may only end up dumping excessive heat into the joint and damaging the components while you fuss over perfect fillets. A well-made solder joint that just covers the pad and makes good contact to the lead on one side of the board, is good enough.

Building your own electronic equipment is seldom cheaper than buying equivalent commercial products, due to commercial economies of scale from which you as small-scale home builder cannot benefit. If you think getting into DIY construction is a way to save money, you will probably be disappointed.

Bill of materials

This table is not a substitute for the text instructions.

Qty	Ref	Value/Part No.	
9	C10–C12, C24–C26, C39–C41	100pF	radial ceramic, 0.2″ lead spacing
2	C5, C19	1200pF	film, 0.2″ lead spacing
2	C15, C16	6800pF	film, 0.2″ lead spacing
25	C1–C4, C6–C9, C13, C14, C17, C18, C20–C23, C27, C28, C32–C38	0.1μF	axial ceramic
3	C29–C31	10μF	radial aluminum electrolytic, 0.1″ lead spacing
1	D3	1N4148	or 1N914; switching diode
2	D6, D7	1N5818	or SB130; Schottky rectifier
7	D1, D2, D4, D5, D8–D10	1N5231B	5.1V Zener
8	H9–H16	M3x6	M3 machine screw, 6mm body length
4	H17–H20		nylon washer for M3 machine screw
4	H21–H24	M3x10	M3 male-female standoff, 10mm body length
4	H25–H28	M3x11	M3 male-female standoff, 11mm body length
4	H29–H32		nut for M3 machine screw
20	J1–J20	1502 03	switched mono 3.5mm panel jack, Lumberg
3	J21–J23		female single-row socket, 10 pins at 0.1″
1	P1		male Eurorack power header, 2×8 pins at 0.1″, right angle
3	P2–P4		male single-row header, 10 pins at 0.1″
1	Q1	THAT320	quad PNP transistor array
13	Q4–Q16	2N3904	NPN general purpose amplifier, TO-92 EBC
2	Q2, Q3	2N7000	N-channel enhancement MOSFET, TO-92 SGD
4	R12, R48, R76, R80	100Ω	
4	R11, R47, R75, R79	270Ω	
13	R93–R105	680Ω	
14	R20, R23, R31, R36, R58, R61, R69, R74, R83, R127, R134, R139, R141, R142	1kΩ	
8	R15, R17, R18, R21, R53, R55, R56, R59	2.7kΩ	
7	R13, R22, R49, R50, R60, R78, R82	6.8kΩ	
2	R14, R52	8.2kΩ	
2	R25, R63	10kΩ	horizontal single turn, Vishay T73YP or similar

Qty	Ref	Value/Part No.	
4	R19, R51, R57, R77	10kΩ	
2	R27, R65	12kΩ	
12	R116–R119, R123, R124, R128–R131, R135, R136	18kΩ	
1	R122	22kΩ	
2	R24, R62	24kΩ	
10	R28–R30, R66–R68, R91, R92, R120, R121	27kΩ	
2	R26, R64	36kΩ	
8	R16, R54, R125, R126, R132, R133, R137, R138	39kΩ	
2	R10, R46	50kΩ	horizontal multiturn, Bourns 3296P/Vishay T93Z
2	R32, R70	56kΩ	
1	R90	68kΩ	
2	R4, R40	91kΩ	
11	R3, R5, R7, R34, R39, R41, R43, R72, R85, R87, R89	100kΩ	vertical conductive plastic panel pot, BI Technologies P0915N series, linear taper
24	R1, R2, R8, R33, R35, R37, R38, R44, R71, R73, R84, R86, R88, R106–R115, R140	100kΩ	
2	R9, R45	130kΩ	
1	R81	1MΩ	
2	R6, R42	1.8MΩ	
1	S1	100SP3T1B1M1QEH	E-Switch 100-series SPDT on-off-on toggle
5	U1–U5	TL074	quad JFET-input op amp
2	U6, U7	AD633	analog multiplier
3	U8–U10	LF353	dual JFET-input op amp
2	U11, U12	LM13700	dual operational transconductance amp
1	U13	78L09	+9V regulator in TO-92 package
5	Q1, U2–U5		14-pin DIP socket
5	U6–U10		8-pin DIP socket
2	U11, U12		16-pin DIP socket

Fixed resistors should be 1% metal film throughout. RoHS-certified zinc-plated steel hardware is recommended, not stainless steel because of galvanic-corrosion incompatibility with aluminum parts.

Note some kits may substitute parts of equivalent or better specifications, in particular 1N5231C Zener diodes and TL074B op amps.

Also needed: solder and related supplies, PCB, panel, knobs, 16-pin Eurorack power cable, etc.

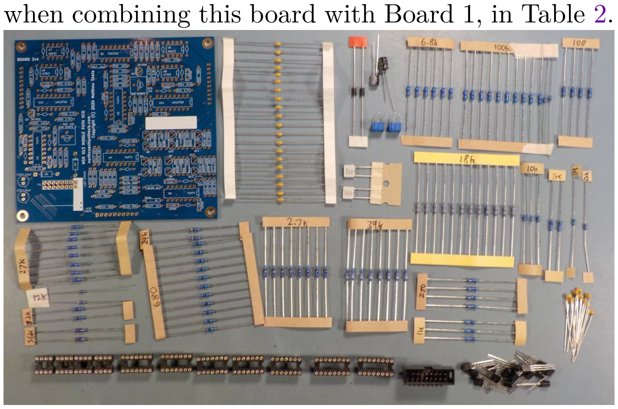
Building Board 2

The recommended order for building this module is to assemble Board 2, the one further from the front panel, first. That will make it easier to get all the physical positioning right for the components that bridge between the boards or pass through the panel.

Note that although I'm describing a separate step for each component value, and that's how I built my prototype so as to have plenty of photo opportunities, if you are reasonably confident about your skills you may find it easier to populate all or most of the board (i.e. put the components in place) and then solder them in a single step. Except where noted, the order in which you add components does not matter much.

Preliminaries

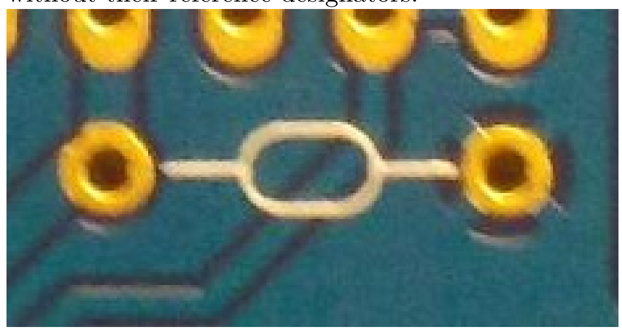
Count out the right number of everything according to the bill of materials. There is an abbreviated BOM for Board 2, excluding a few items that will be added when combining this board with Board 1, in Table 2.



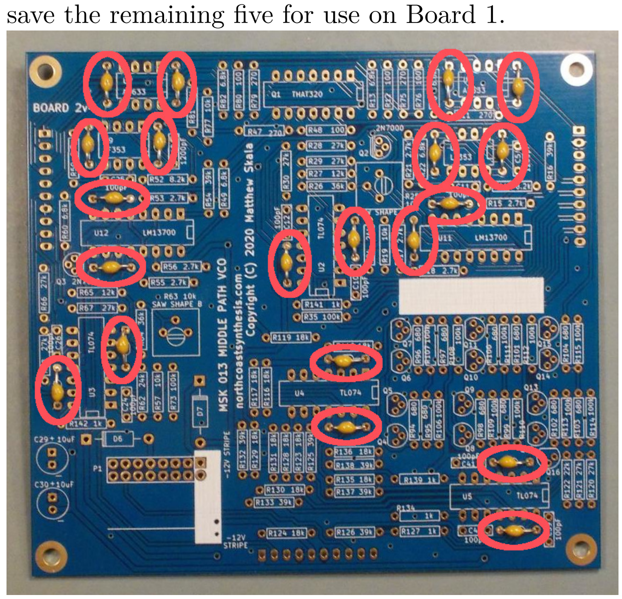
The components for this board include 2N7000 MOSFETs, which are static-sensitive. You should take anti-static precautions with these. They should be supplied in anti-static packaging. Leave them in that packaging until you need to use them, and work on an anti-static surface, with a grounding wrist strap, or both, while handling these components. After the MOSFETs are installed, assuming the resistors were installed first as recommended, the resistors will provide some protection for these MOSFETs, reducing the necessary precaution level. North Coast kits include spare MOSFETs just in case.

Decoupling capacitors

The 20 axial ceramic 0.1μF decoupling capacitors, C1–C4, C6–C9, C13, C14, C17, C18, C20–C23, and C35–C38, are shown on the board by a special symbol without their reference designators.



Install these capacitors where the symbol appears. They are not polarized and may be installed in either orientation. These capacitors act as filters for the power supplies to the integrated circuits. An MSK 013 kit should include 25 of these capacitors; save the remaining five for use on Board 1.



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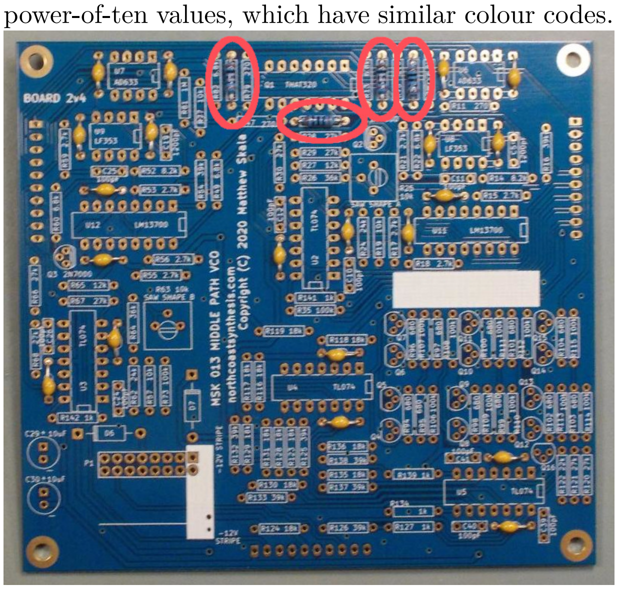
2	C5, C19	1200pF	film, 0.2″ lead spacing
20	C1–C4, C6–C9, C13, C14, C17, C18, C20–C23, C35–C38	0.1μF	axial ceramic
2	C29, C30	10μF	radial aluminum electrolytic, 0.1″ lead spacing
2	D6, D7	1N5818	or SB130; Schottky rectifier
1	P1		male Eurorack power header, 2×8 pins at 0.1″, right angle
13	Q4–Q16	2N3904	NPN general purpose amplifier, TO-92 EBC
2	Q2, Q3	2N7000	N-channel enhancement MOSFET, TO-92 SGD
4	R12, R48, R76, R80	100Ω	
4	R11, R47, R75, R79	270Ω	
11	R94–R104	680Ω	
5	R127, R134, R139, R141, R142	1kΩ	
8	R15, R17, R18, R21, R53, R55, R56, R59	2.7kΩ	
6	R13, R22, R49, R60, R78, R82	6.8kΩ	
2	R14, R52	8.2kΩ	
2	R25, R63	10kΩ	horizontal single turn, Vishay T73YP or similar
3	R19, R57, R77	10kΩ	
2	R27, R65	12kΩ	
12	R116–R119, R123, R124, R128–R131, R135, R136	18kΩ	
1	R122	22kΩ	
2	R24, R62	24kΩ	
8	R28–R30, R66–R68, R120, R121	27kΩ	
2	R26, R64	36kΩ	
8	R16, R54, R125, R126, R132, R133, R137, R138	39kΩ	
12	R35, R73, R106–R115	100kΩ	
1	R81	1MΩ	
5	Q1, U2–U5		14-pin DIP socket
4	U6–U9		8-pin DIP socket
2	U11, U12		16-pin DIP socket

Table 2: Bill of Materials for assembling Board 2 – excluding a few that are better added later, during the Board 1 build. Also needed is the PCB itself.

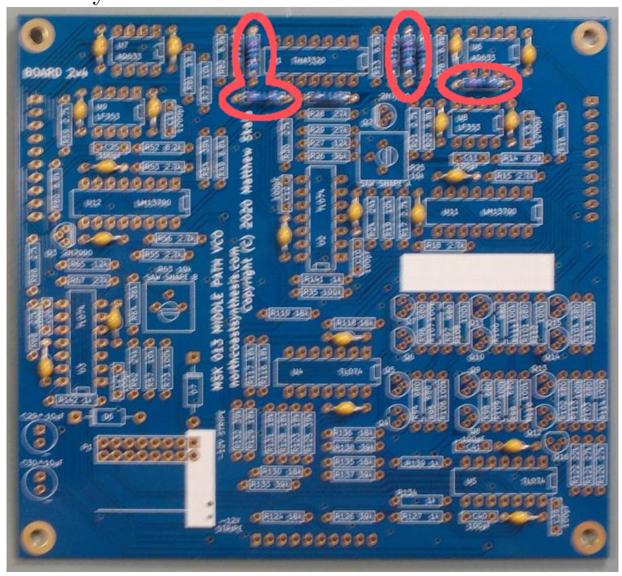
Fixed resistors

Resistors are never polarized. I like to install mine in a consistent direction for cosmetic reasons, but this is electrically unnecessary. In this module, the fixed resistors are metal film 1% type. They usually have blue bodies and four colour bands designating the value, plus a fifth band for the tolerance. The tolerance band is brown for 1%, but note that we may occasionally ship better-tolerance resistors in the kits than the specifications require, if we are able to source them at a good price. Accordingly, I mention only the four value band colours for this type of resistor; if you are using resistors with other codes, you are responsible for knowing them. Note that colour codes on metal film 1% resistors are often ambiguous (reading from one end or the other end may give two different values, both plausible) and some of the colours are hard to distinguish anyway. If in doubt, always measure with an ohmmeter before soldering the resistor in place.

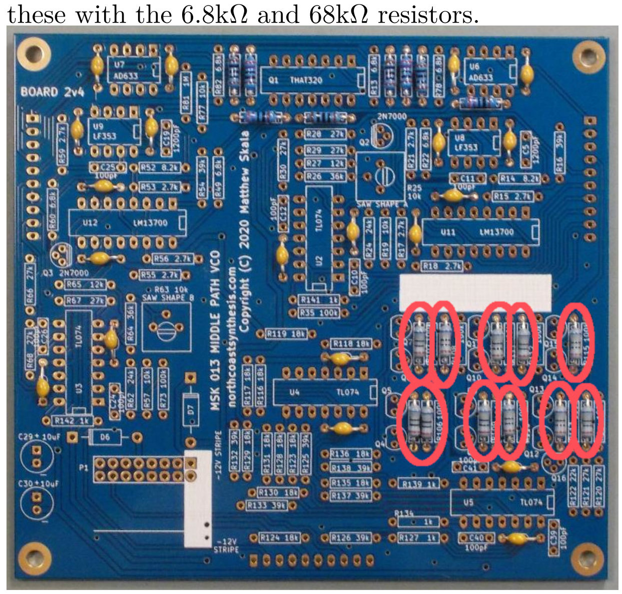
Install the four 100Ω (brown-black-black-black) resistors R12, R48, R76, and R80. These resistors are used to reduce the voltage applied to transistor bases in the exponential converter, allowing the analog multiplier to operate in a more comfortable voltage range. Do not confuse them with 1kΩ and other power-of-ten values, which have similar colour codes.



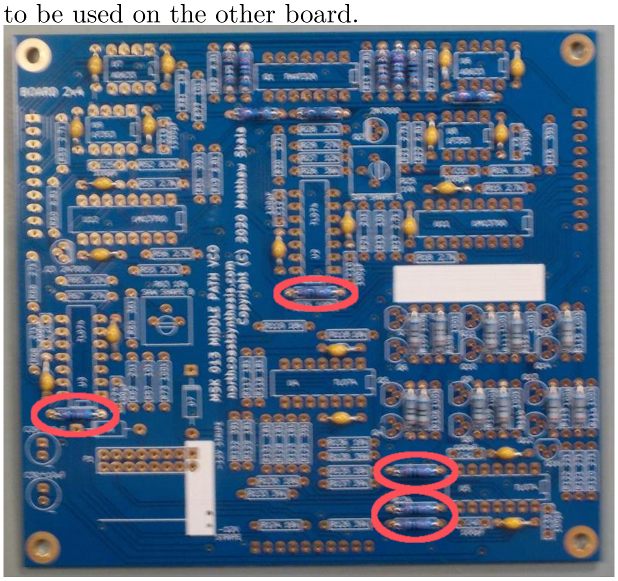
Install the four 270Ω (red-violet-black-black) resistors R11, R47, R75, and R79. These form the other sides of the four transistor-base voltage dividers, with the 100Ω resistors. Do not confuse them with the similarly-coded 2.7kΩ and 27kΩ resistors.



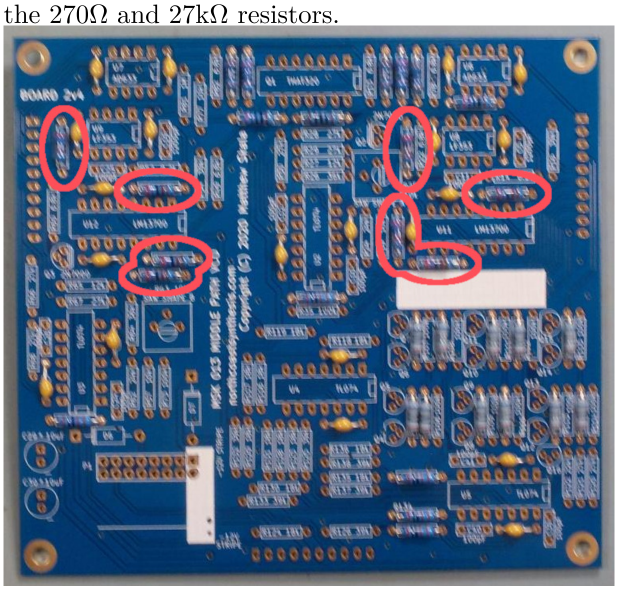
Install the eleven 680Ω (blue-grey-black-black) resistors R94–R104. These form a chain across the bases of the discrete transistors in the sine shaper, allowing the input voltage to be applied in different amounts to all the transistors. Note that a complete kit includes thirteen 680Ω resistors; save the remaining two to install on the other board. Do not confuse these with the 6.8kΩ and 68kΩ resistors.



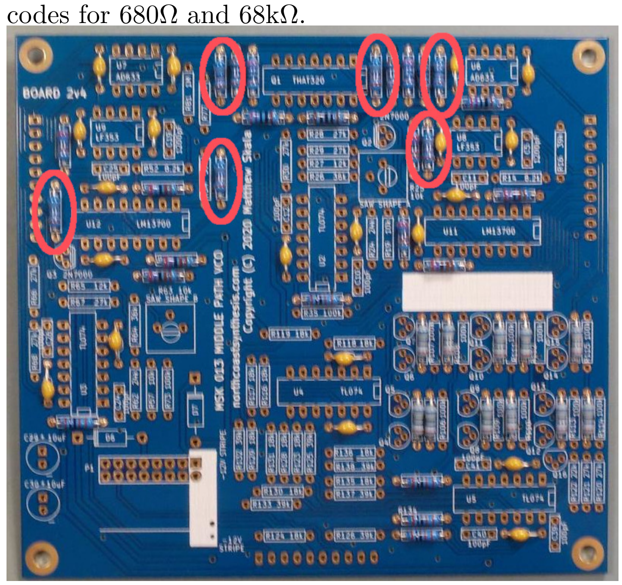
Install the five 1kΩ (brown-black-black-brown) resistors R127, R134, R139, R141, and R142. These are used on op amp outputs in the sine and pulse shapers, to limit current and improve stability. Do not confuse them with other power-of-ten values, like 100Ω and 10kΩ. A kit should contain nine more 1kΩ resistors to be used on the other board.



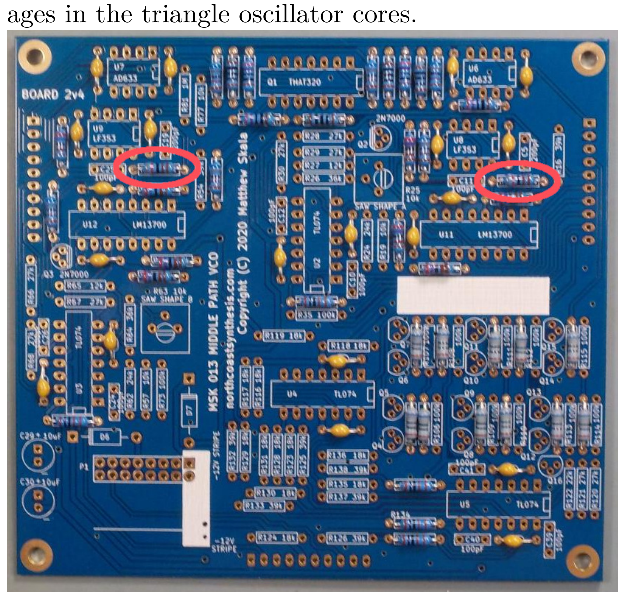
Install the eight 2.7kΩ (red-violet-black-brown) resistors R15, R17, R18, R21, R53, R55, R56, and R59. Most of these are used for controlling signal levels in the triangle oscillator cores; R21 and R59 set the gain, and thus the output signal level, for the square output amplifiers. Do not confuse them with the 270Ω and 27kΩ resistors.



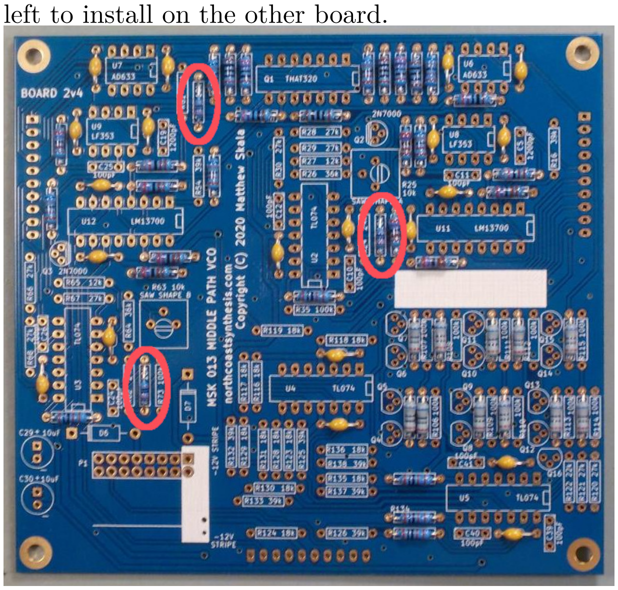
Install the six 6.8kΩ (blue-grey-black-brown) resistors R13, R22, R49, R60, R78, and R82. The resistors R22 and R60 set gain for the square wave outputs; the rest control current levels and ensure symmetric loading in the exponential converter, with one resistor on the collector of each transistor in Q1. One 6.8kΩ resistor should remain to install on Board 1. Do not confuse these resistors with the similar colour codes for 680Ω and 68kΩ.



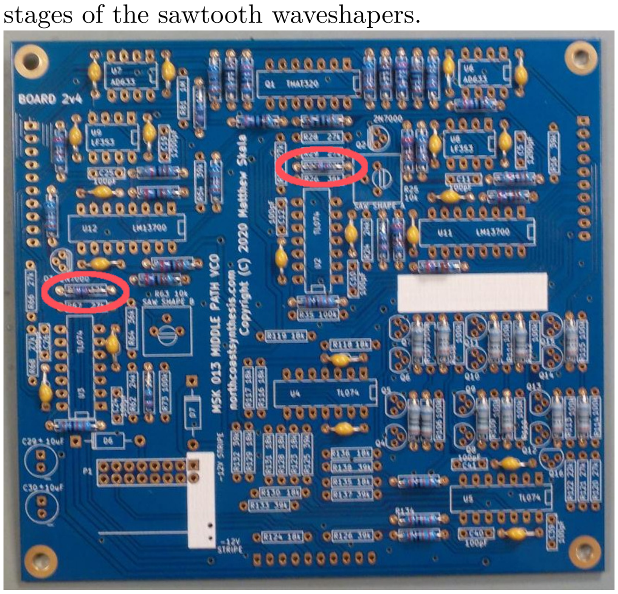
Install the two 8.2kΩ (grey-red-black-brown) resistors R14 and R52. These form parts of voltage dividers that scale down the comparator input voltages in the triangle oscillator cores.



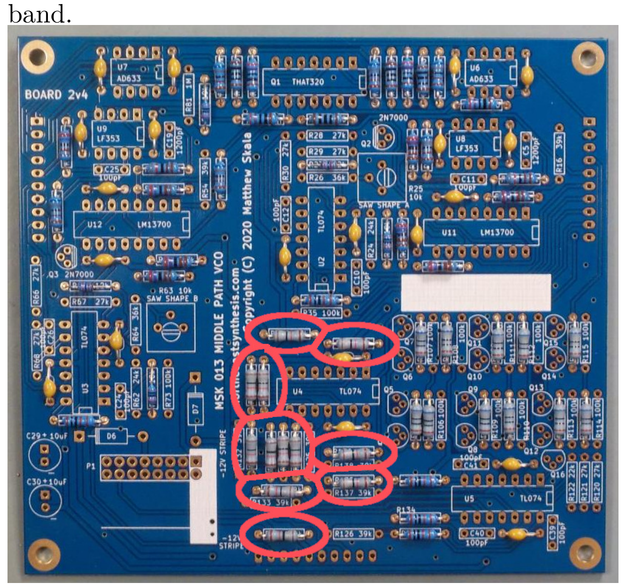
Install the three 10kΩ (brown-black-black-red) resistors R19, R57, and R77. R77 sets the high reference current for the exponential converter; the others are feedback resistors for the triangle output buffer amplifiers. Do not confuse these with other power-of-ten resistor values. One 10kΩ resistor should be left to install on the other board.



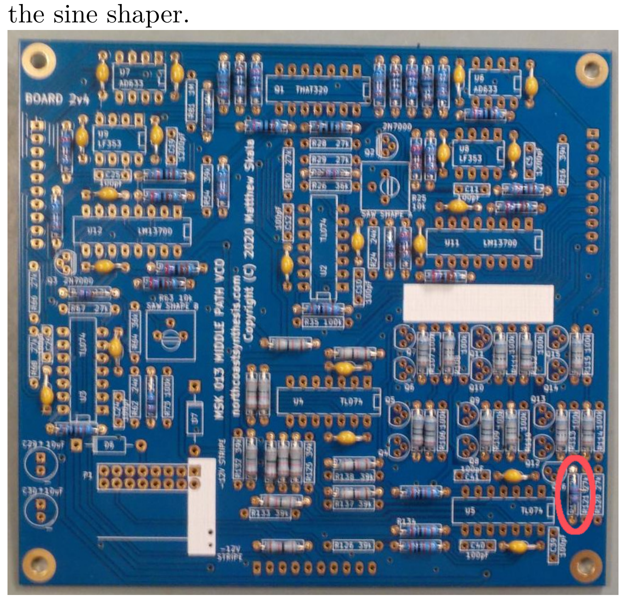
Install the two 12kΩ (brown-red-black-red) resistors R27 and R65. These set the gain for the first stages of the sawtooth waveshapers.



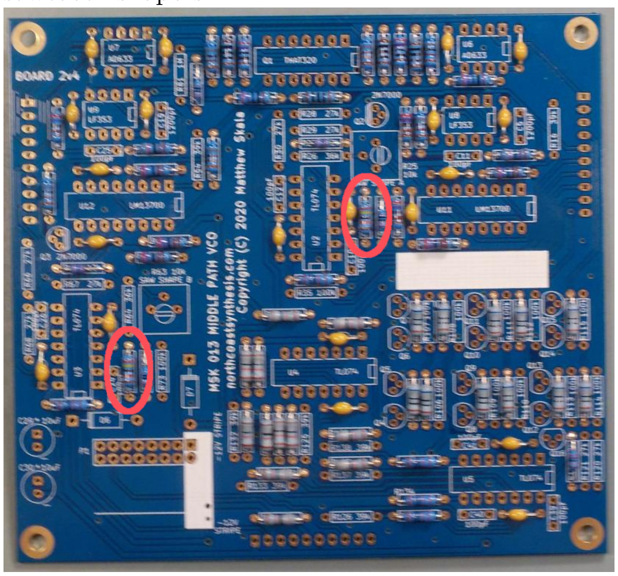
Install the twelve 18kΩ (brown-grey-black-red) resistors R116–R119, R123, R124, R128–R131, R135, and R136. These set currents and gains throughout the sine shaper. Do not confuse them with the 1.8MΩ resistors, whose colour codes differ only in the fourth band.



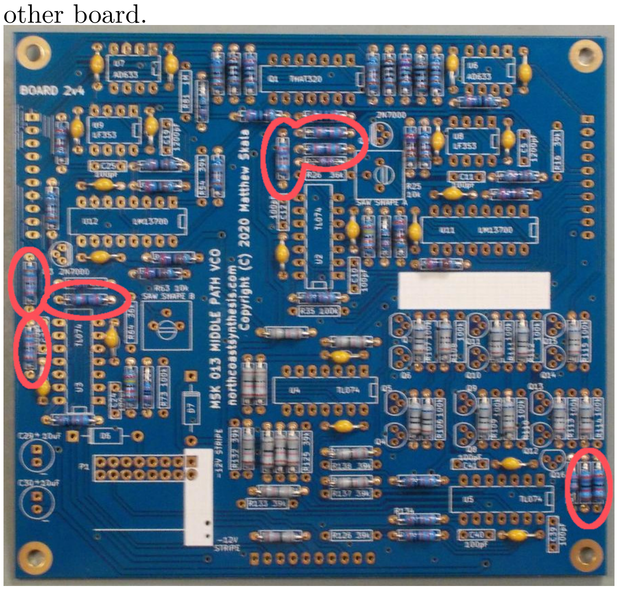
Install the single 22kΩ (red-red-black-red) resistor R122. This sets the global reference current level for the sine shaper.



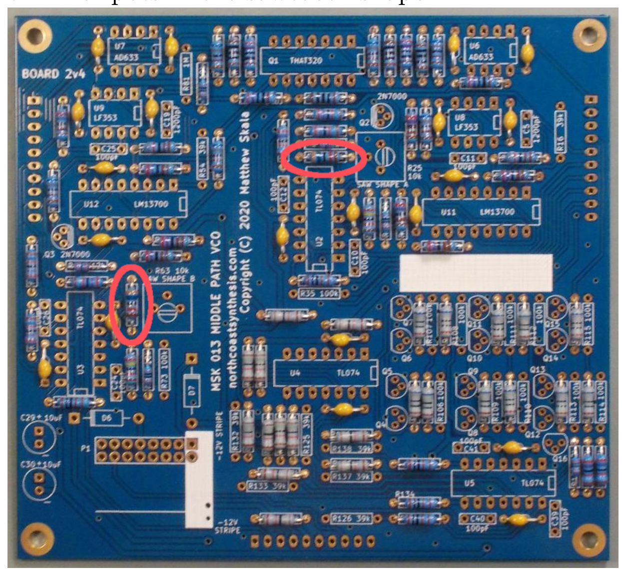
Install the two 24kΩ (red-yellow-black-red) resistors R24 and R62. These set the input levels for the sawtooth shapers.



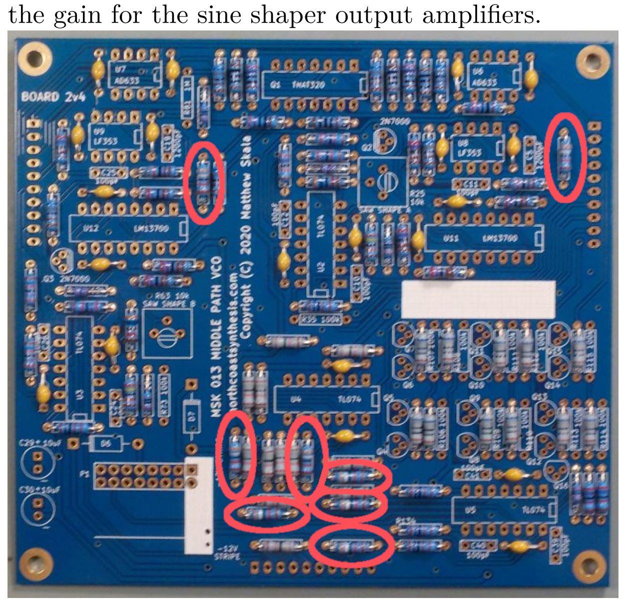
Install the eight 27kΩ (red-violet-black-red) resistors R28–R30, R66–R68, R120, and R121. Most of these resistors set gain in the sawtooth shapers; R120 and R121 form a divider that controls the global current level in the sine shaper. Do not confuse these with the 270Ω and 2.7kΩ resistors. There should be two more 27kΩ resistors remaining to install on the other board.



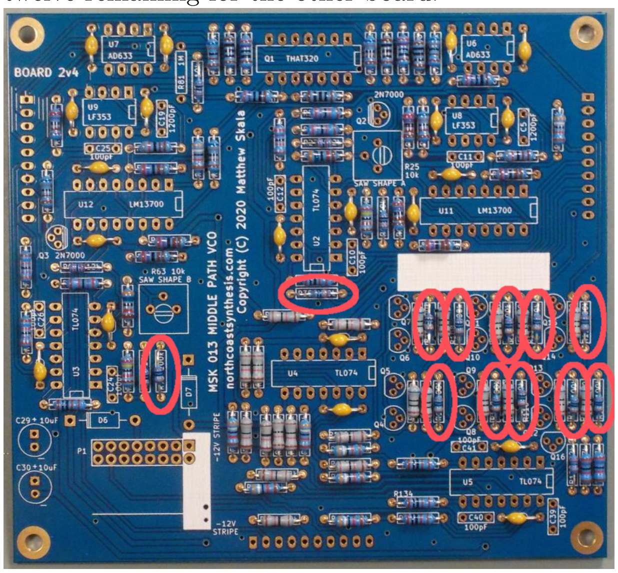
Install the two 36kΩ (orange-blue-black-red) resistors R26 and R64. These set the range for the trimmer pots in the sawtooth shaper.



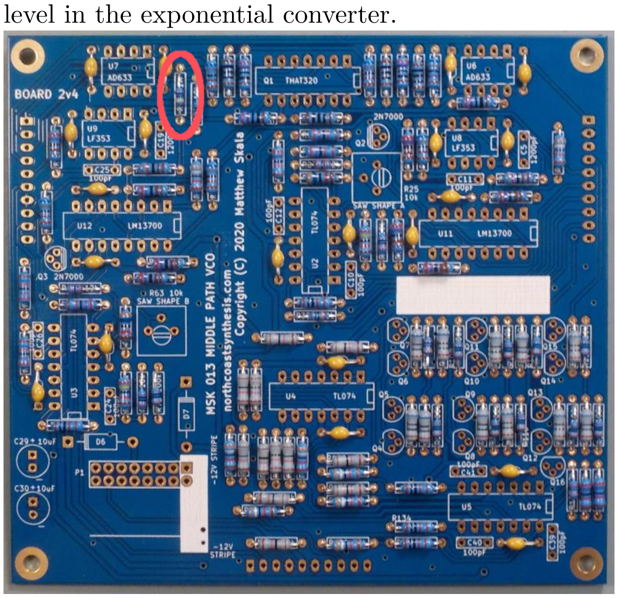
Install the eight 39kΩ (orange-white-black-red) resistors R16, R54, R125, R126, R132, R133, R137, and R138. The first two of these (R16 and R54) set the control currents for the comparators in the triangle oscillator cores. The remaining 39kΩ resistors set the gain for the sine shaper output amplifiers.



Install the twelve 100kΩ (brown-black-black-orange) resistors R35, R73, and R106–R115. The first two of these (R35 and R73) provide high-impedance connections from the triangle cores to the pulse shapers. The rest are used in the sine shaper to trickle a little bit of current into transistor bases at points spread out along the chain. Do not confuse these 100kΩ resistors with other power-of-ten values. A full kit contains 24 of these resistors; there should be twelve remaining for the other board.

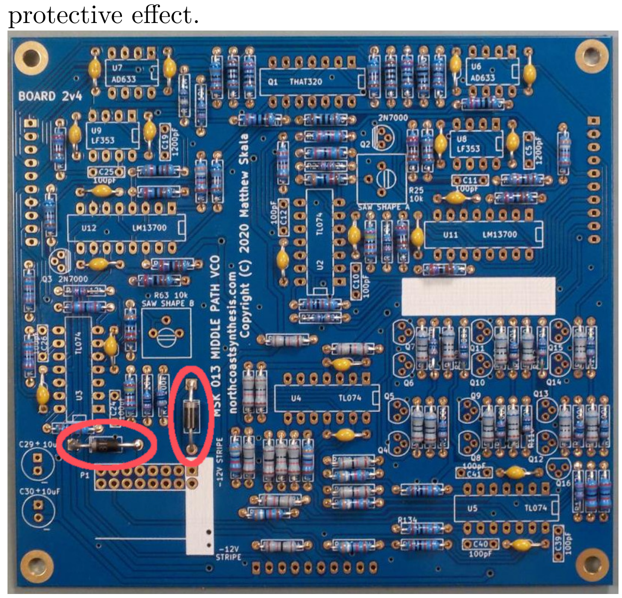


Install the single 1MΩ (brown-black-black-yellow) resistor R81. Do not confuse it with other power-of-ten values. This resistor sets the low reference current level in the exponential converter.

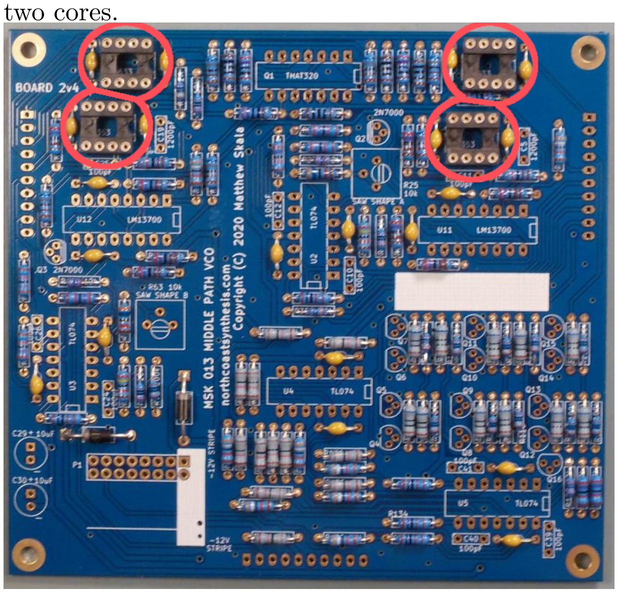


Diodes and DIP sockets

Install the two 1N5818 or SBA130 Schottky rectifier diodes D6 and D7. These are for reverse-voltage protection. Since this module uses 16-pin power, the possible kinds of bad connection are more complicated than with a standard 10-pin power connection, and these diodes will not solve all possible problems, but they still help. They are polarized and it is important to install them in the right direction. Each diode is packaged inside a black or dark grey plastic slug with a white or light grey stripe at one end; that end is the *cathode*. The silkscreen markings on the board have a corresponding stripe and the diodes should be installed with their stripes matching the markings on the board. The solder pads for the cathodes are also square instead of round. Installing these backwards means they will have the opposite of the intended protective effect.



Install the four 8-pin DIP sockets for the analog multipliers U6 and U7, and the dual operational amplifier chips U8 and U9. The analog multipliers are used in the exponential converter to calculate temperature-compensated control voltages; they are very expensive chips, about Ca$16 each as of this writing, so I would certainly recommend using sockets for these chips even if you are trying to dispense with sockets on other chips. The LF353 dual op amps are used in the oscillator cores instead of quads, to help reduce any possibility of cross talk between the two cores.

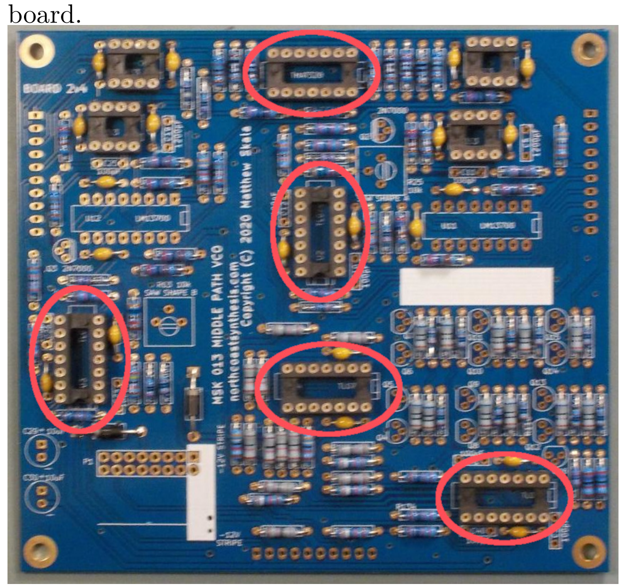


DIP sockets themselves do not care which direction you install them, but it is critically important that the chips installed in the sockets should be installed in the right direction. To help with that, the sockets will probably be marked with notches at one end (indicating the end where Pin 1 and Pin 14 are located) and you should install the sockets so that the notched ends match the notches shown on the PCB silkscreen. The solder pad for Pin 1 is also distinguished by being rectangular instead of rounded.

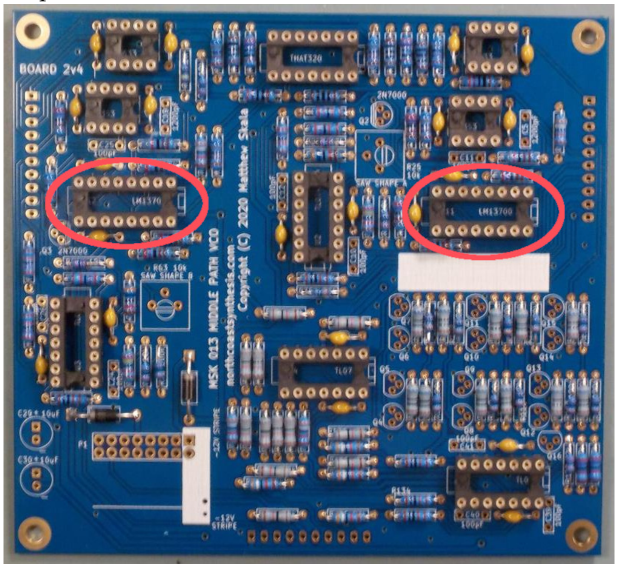
Installing DIP sockets without having them tilted at a funny angle can be tricky. I recommend inserting the socket in the board, taping it in place on the component side with vinyl electrical tape or sticking it there with a small blob of putty at each end, then soldering one pin on one corner and checking that the socket is snug against the board before soldering the other pins. That way, if you accidentally solder the first pin with the socket tilted, it will be easier to correct (only one pin to desolder instead of all of them).

If you somehow manage to solder an entire socket in backwards, don't try to desolder it to turn it around. Just leave it as it is and remember that when you insert the chip, you must insert it so the chip matches the markings on the *board*, not the turned-around socket.

Install the five 14-pin DIP sockets for the transistor array Q1 and the four quad operational amplifiers U2–U5. The THAT320 transistor array (another expensive chip) is the heart of the exponential converter: two reference transistors and two current-sourcing transistors all on a single chip, keeping them all at the same temperature for accurate tracking. The quad op amps are general analog building blocks used throughout the waveshapers and buffers on this board.



Install the two 16-pin DIP sockets for the operational transconductance amplifiers U11 and U12. Each of these provides a comparator and a current amplifier for one oscillator core.

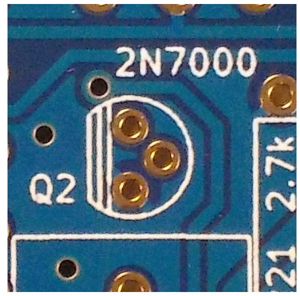


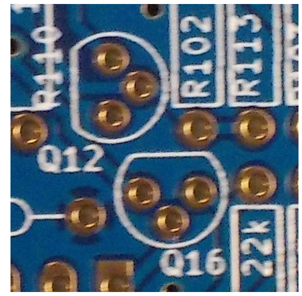
TO-92 semiconductors

The MSK 012 contains three different types of components packaged in TO-92 packages, of which two types are used on Board 2. Each TO-92 component looks like a little black pill of epoxy plastic with one flat side and three metal legs; they can be distinguished by etched or printed numbers on the flat side, and it is important to sort them carefully and install only the proper component type in each footprint.

As described in the “Preliminaries” section, the 2N7000 MOSFETs are static-sensitive. I recommend doing the component-sorting and then *returning the MOSFETs to their anti-static packaging* until use, rather than leaving them exposed.

There is not enough space on the boards to print a part number for every TO-92 component, but there are two different silkscreen symbols used to help with recognition. The 2N7000 MOSFETs are shown on the board with extra silkscreen lines along the flat edge, as in the left photo. All other TO-92 components (2N3904 on Board 2, and 78L09 on Board 1) are shown by a plain outline without extra lines, as in the right photo. Note these two photos are just to illustrate the symbols; they were actually taken on MSK 007 Leapfrog boards.

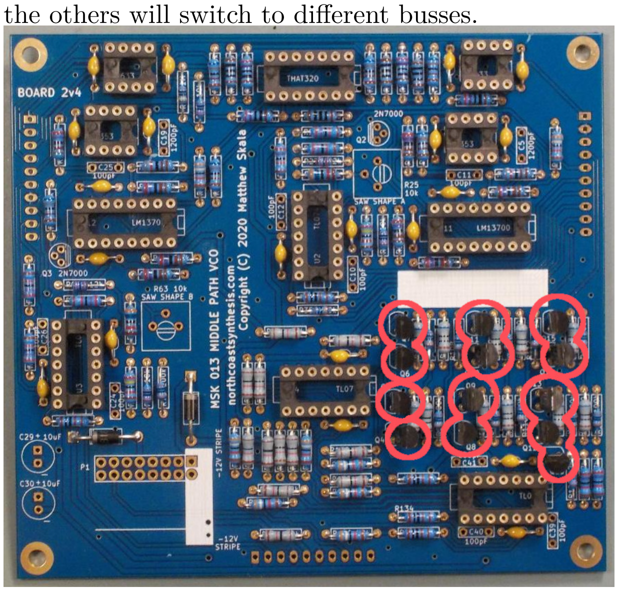




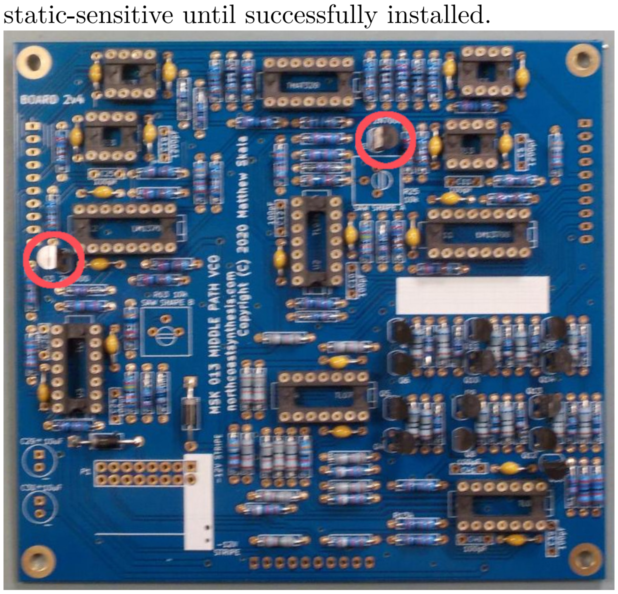
All TO-92 components in this project are polarized and must be installed in the correct orientation to work; that orientation is shown by the silkscreen symbols. Install each component so that its flat side points in the same direction as the flat side shown on the silkscreen. The three legs of the component must be carefully bent into the same triangular pattern (left and right forward, middle backward) as the holes on the board, and then the component pressed into place. There should be a gap of about three millimetres between the board and the component body; do not attempt to seat the component flush on the board because of the risk of breaking off the legs where they enter the body.

The solder pads for these components are smaller and closer together than for any other through-hole components in the project, and the components themselves tend to be relatively heat-sensitive. Solder them carefully, avoiding creating any solder bridges between adjacent pads. Do not use excessive time and heat trying to get the solder to flow through the board and fillet on both sides, especially not on pads connected to the ground plane; two-sided fillets may happen naturally, but it is enough for solder to completely cover the pad on one side. Excess heat on the pads in the sine shaper, in particular, causing pads to lift off the boards, was a significant problem in some of my prototype builds with rush-production boards. The boards supplied in kits ought to be higher quality and have less risk of this issue, but it still requires caution.

Install the thirteen 2N3904 transistors Q4–Q16. These make up the core of the sine shaper: a grid of twelve transistors that correspond to different voltage levels in the input, and one more transistor used as a current source to provide the reference current that the others will switch to different busses.



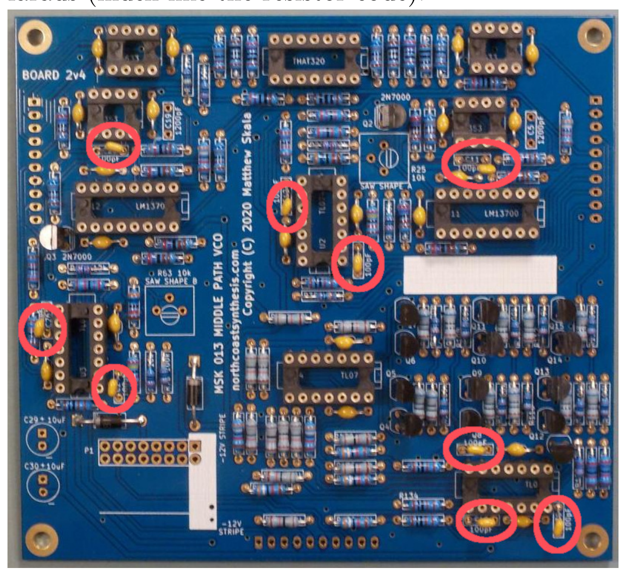
Install the two 2N7000 MOSFETs Q2 and Q3. These are low-resistance switches used in the triangle to sawtooth shapers. As described above, they are static-sensitive until successfully installed.



One TO-92 component should be left over after building Board 2: the 78L09 regulator that will be installed later on Board 1.

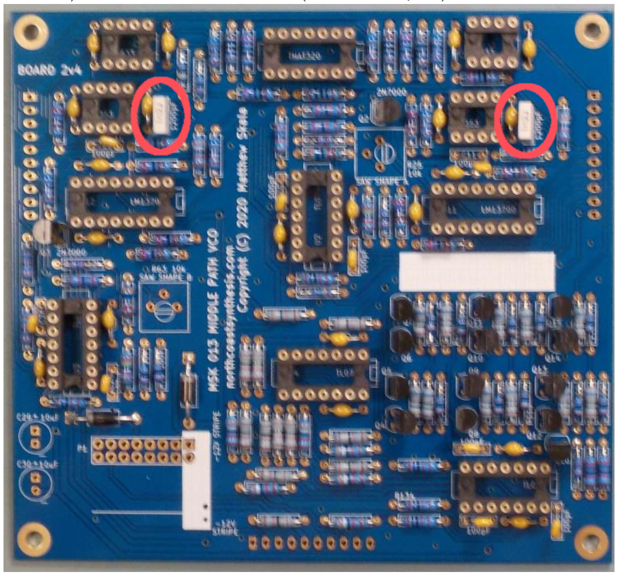
More capacitors

Install the nine 100pF ceramic capacitors C10–C12, C24–C26, and C39–C40. These are compensation capacitors used to ensure stability on op amps that have outputs exposed to the outside world. They are unpolarized and may be installed in either orientation. Note that although this photo shows yellow capacitors that were used in early assembled-module builds, most kits will ship with blue capacitors. The capacitors are likely to be marked "101" for the digits 10 followed by one more 0, that is 100, number of picofarads (much like the resistor code).

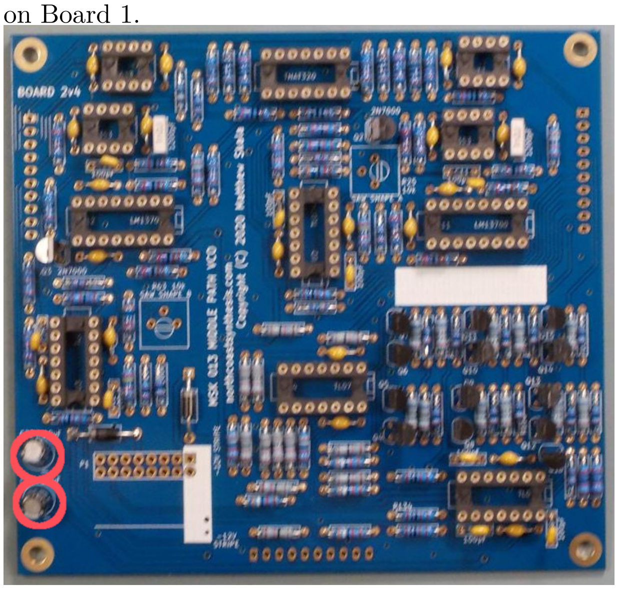


Install the two 1200pF film capacitors C5 and C19. These are the timing capacitors for the oscillator cores. They are unpolarized and may be installed in either direction. The markings on film capacitors vary depending on the manufacturer and model.

These ones might be marked “122” (for 12 followed by two 0s number of picofarads), “1n2” (for 1.2nF), or even “0.0012” (value in μF).



Install the two 10μF electrolytic capacitors C29 and C30, which filter the power supply for the module as a whole. These are polarized components and they may explode if installed backwards. Each one will be marked on its casing with a stripe and minus signs to indicate the negative lead; the positive lead will probably also be longer. These clues should be matched with the markings on the PCB: plus and minus symbols in the silkscreen and a square solder pad for the positive (long) lead. There should be one more 10μF electrolytic capacitor remaining, for use on Board 1.

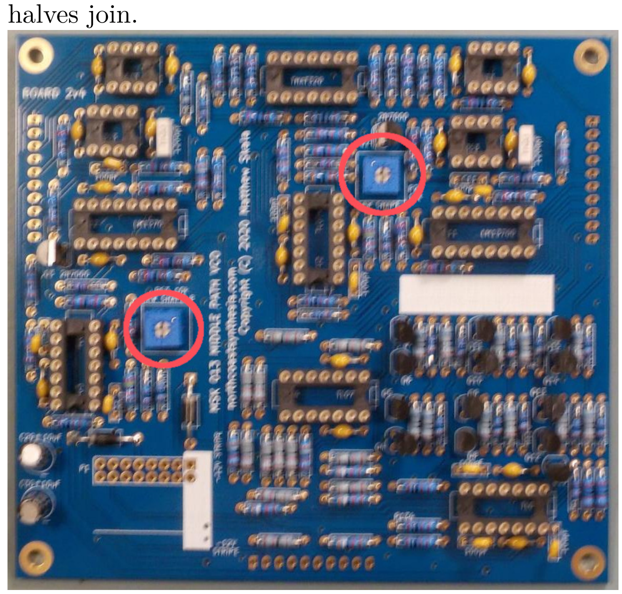


Trimmer potentiometers

Trimmers usually are not washable, so if you plan to clean your boards by full immersion in water or other solvent, your last chance is now; future cleaning will have to be done with a brush and some care to avoid letting liquid seep into the trimmers. Even now you should take some care with the DIP sockets, because although they are in principle washable, solvent can carry flux residue into the sockets and form a varnish-like layer if not carefully rinsed away.

Trimmers are not exactly polarized, but the three legs of each trimmer serve different functions and need to be connected to the right holes. The physical arrangement of the legs and corresponding holes should make it impossible to install the trimmers wrong way round.

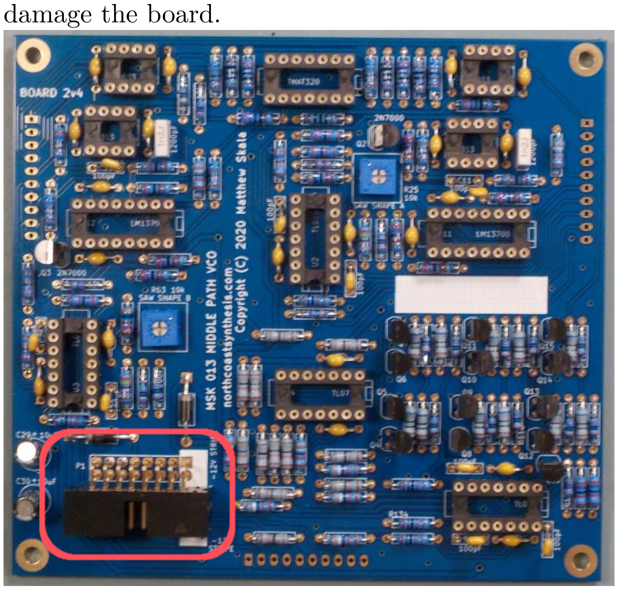
Install the two 10kΩ single-turn trimmers R25 and R63. These trimmers adjust the voltage offset between the first and second halves of the sawtooth wave, so that you can null out the glitch where the halves join.



Eurorack power connector

Install the 2×8-pin Eurorack power connector P1. This connector is polarized, and although the pad footprint is symmetrical, installing the connector in anything but the correct orientation would cause it to interfere with the Schottky diodes, so there is little risk of getting it wrong. As with the DIP sockets, you should be careful to get it installed snugly against the board, not tilted at an angle. Use tape or putty to hold it in place, solder one pin, then check that it is straight before you solder the other pins.

Beware of solder bridges among the pins of the 16-pin power connector. Many of the pins are deliberately connected together anyway, and bridges among those pins are harmless enough, but unless you are sure you know which ones the connected-together pins are, it is advisable to remove all solder bridges. I recommend using a wider tip on the soldering iron because the connector pins are heavy and require more heat than most other components, but it remains important not to use excessive heat and damage the board.



A little more assembly is required for Board 2, namely installing the pin headers for connecting to Board 1, and inserting the DIP ICs in their sockets, but it is more convenient to do those steps later as part of the Board 1 and final assembly.

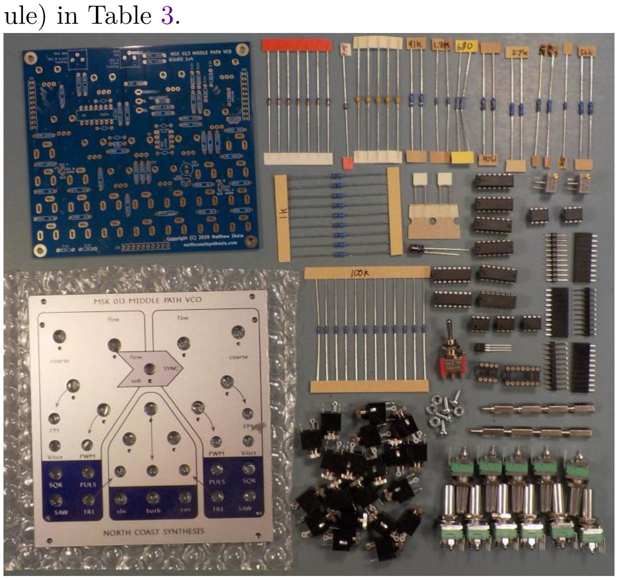
In between completed boards is a good time to take a break.

Building Board 1

Board 1 has components on both sides, and for best results, it is important to install them in the right order. Build Board 2 first, and see the general comments in the Board 2 chapters about how to approach the task.

Preliminaries

Count out the right number of everything according to the bill of materials. There is an abbreviated BOM for the items needed in this chapter (including the connection to Board 2 and final assembly of the module) in Table 3.



Some notes on knobs

The first batch of knobs I ordered for North Coast products turned out to have serious quality problems, specifically with the setscrews that hold the knobs onto the potentiometer shafts. Some of the screws had marginal threads that would strip when the screw was tightened, and I ended up having to do a bunch of extra testing and ship extra knobs to some customers to replace any that might fail. Later batches have also had issues, although they're under better control now because the bad first batch served as a warning to step up the testing procedures.

Starting with kits prepared in August 2019 (including all Middle Path VCO kits), I switched to blue knobs with 100% testing; in September 2020, I switched to a new manufacturer, and knobs that are a slightly darker shade of blue. Although all the knobs I ship in kits now have been tested and passed at least twice, and should be fine to use, I am also shipping spare setscrews in any kits with knobs from batches where a signficant number of knobs failed testing.

Normalization selection

In a standard build, the V/oct input of the master oscillator is normalized to the Eurorack bus CV, and that of the slave oscillator is normalized to the V/oct input of the master oscillator. As a result, the control scheme for the two oscillators works as follows.

- With no cables plugged into the V/oct jack sockets: both oscillators controlled by bus CV.
- With a cable plugged into the master V/oct jack socket only: both oscillators controlled by the cable CV.
- With a cable plugged into the slave V/oct jack socket only: master controlled by bus CV, slave by the cable CV.
- With cables pluegged into both V/oct jack sockets: each oscillator controlled by its own cable.

However, if desired you can change these normalizations by cutting and bridging some traces on the Board 1 PCB. For example, if you don't want to use the CV bus, or do want to use it for some other purpose, you could remove the connection to that. In all cases, if a cable is plugged into an oscillator's own V/oct jack socket then the oscillator will use that cable's CV in preference to any other source of V/oct control; the normalization only controls what happens if there is no cable, with options of bus CV, the other oscillator's CV (which could have also come from a normalization), or nothing. Normalizing both oscillators across to each other means they both get the equivalent of 0V when no cables are plugged in, and a single cable plugged into either will control both.

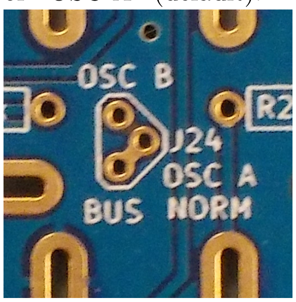
There are two jumper footprints, shown on the

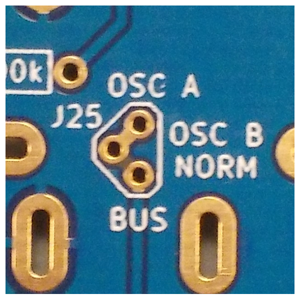
This table is not a substitute for the text instructions.

Qty	Ref	Value/Part No.	
2	C15, C16	6800pF	film, 0.2″ lead spacing
5	C27, C28, C32–C34	0.1μF	axial ceramic
1	C31	10μF	radial aluminum electrolytic, 0.1″ lead spacing
1	D3	1N4148	or 1N914; switching diode
7	D1, D2, D4, D5, D8–D10	1N5231B	5.1V Zener
4	H9–H12	M3x6	M3 machine screw, 6mm body length
4	H21–H24	M3x10	M3 male-female standoff, 10mm body length
4	H25–H28	M3x11	M3 male-female standoff, 11mm body length
4	H29–H32		nut for M3 machine screw
20	J1–J20	1502 03	switched mono 3.5mm panel jack, Lumberg
3	J21–J23		female single-row socket, 10 pins at 0.1″
3	P2–P4		male single-row header, 10 pins at 0.1″
1	Q1	THAT320	quad PNP transistor array
2	R93, R105	680Ω	
9	R20, R23, R31, R36, R58, R61, R69, R74, R83	1kΩ	
1	R50	6.8kΩ	
1	R51	10kΩ	
2	R91, R92	27kΩ	
2	R10, R46	50kΩ	horizontal multiturn, Bourns 3296P/Vishay T93Z
2	R32, R70	56kΩ	
1	R90	68kΩ	
2	R4, R40	91kΩ	
11	R3, R5, R7, R34, R39, R41, R43, R72, R85, R87, R89	100kΩ	vertical conductive plastic panel pot, BI Technologies P0915N series, linear taper
12	R1, R2, R8, R33, R37, R38, R44, R71, R84, R86, R88, R140	100kΩ	
2	R9, R45	130kΩ	
2	R6, R42	1.8MΩ	
1	S1	100SP3T1B1M1QEH	E-Switch 100-series SPDT on-off-on toggle
5	U1–U5	TL074	quad JFET-input op amp
2	U6, U7	AD633	analog multiplier
3	U8–U10	LF353	dual JFET-input op amp
2	U11, U12	LM13700	dual operational transconductance amp
1	U13	78L09	+9V regulator in TO-92 package
1	U1		14-pin DIP socket
1	U10		8-pin DIP socket

Table 3: Bill of Materials for Board 1 and the final assembly of the module. Also needed: the PCB itself, the aluminum front panel, knobs, the assembled Board 2, and panel-to-rack mounting hardware. Note some kits may substitute parts of equivalent or better specifications, in particular 1N5231C Zener diodes and TL074B op amps.

schematic as SPDT switch symbols J24 and J25, for oscillator A (master) and oscillator B (slave) respectively. Each consists of three pads, with the centre pad joined to one of the side pads for the default normalization. Cut that connection to have no normalization (equivalent to being normalized to 0V); cut it and also join the middle pad to the pad on the other side with a bit of wire or a blob of solder, to normalize to the other option. As marked on the board, oscillator A can normalize to "BUS" (default) or "OSC B," and oscillator B can normalize to "BUS" or "OSC A" (default).



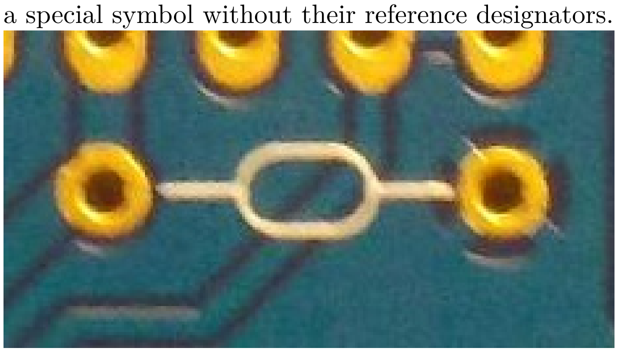


If you want to do this modification then do it now, before installing components on the board. Use an ohmmeter across the pads to check that the connection you intended to break really is broken, and that any connection you intended to add really has become connected.

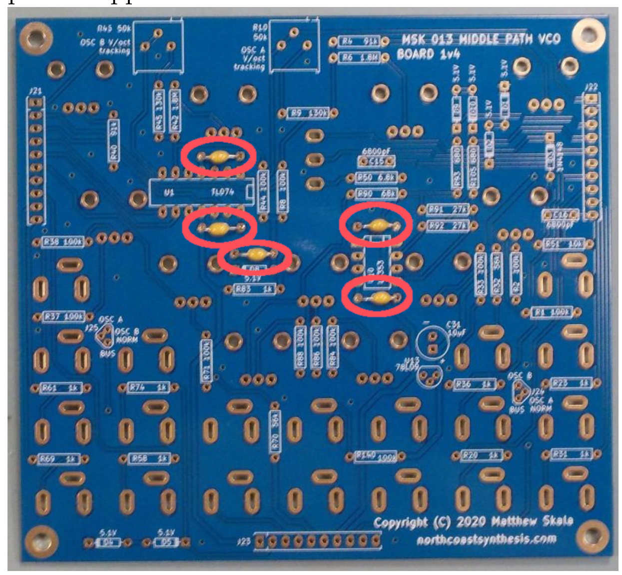
If you sell a modified build, please tell the buyer that it is modified.

Decoupling capacitors

The five axial ceramic 0.1μF decoupling capacitors C28, C28, and C32–C34 are shown on the board by a special symbol without their reference designators.



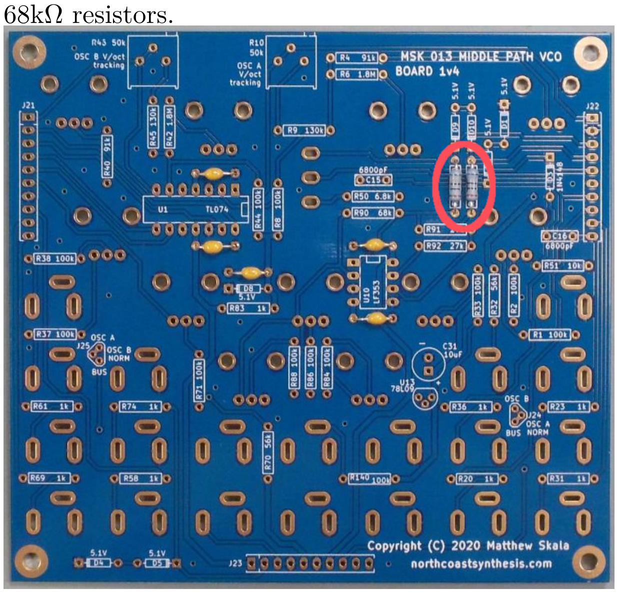
Install these capacitors where the symbol appears. They are not polarized and may be installed in either orientation. These capacitors act as filters for the power supplies.



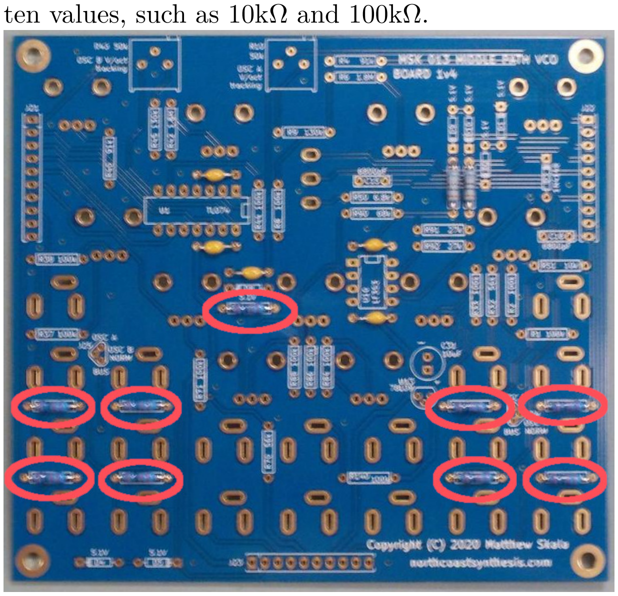
Fixed resistors

Resistors are never polarized. I like to install mine in a consistent direction for cosmetic reasons, but this is electrically unnecessary. In this module, the fixed resistors are metal film 1% type. They usually have blue bodies and four colour bands designating the value, plus a fifth band for the tolerance. The tolerance band is brown for 1%, but note that we may occasionally ship better-tolerance resistors in the kits than the specifications require, if we are able to source them at a good price. Accordingly, I mention only the four value band colours for this type of resistor; if you are using resistors with other codes, you are responsible for knowing them. Note that colour codes on metal film 1% resistors are often ambiguous (reading from one end or the other end may give two different values, both plausible) and some of the colours are hard to distinguish anyway. If in doubt, always measure with an ohmmeter before soldering the resistor in place.

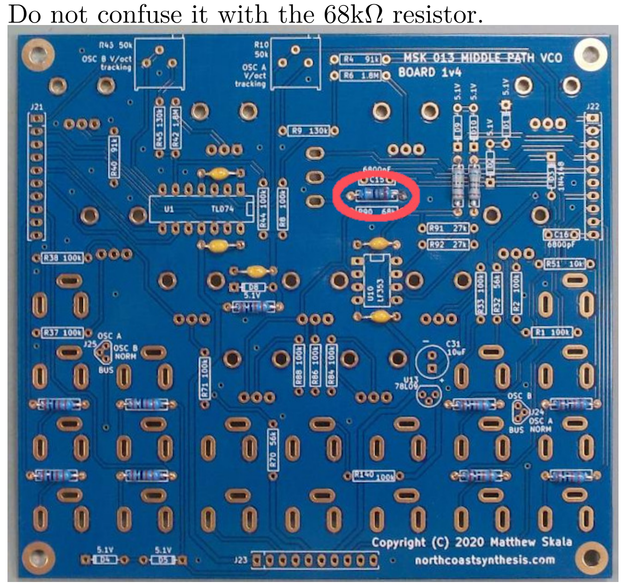
Install the two 680Ω (blue-grey-black-black) resistors R93 and R105. These are the first and last of the resistors in the chain that drives the transistor basis in the sine shaper; the others were already installed on Board 2. Do not confuse them with the 6.8kΩ and 68kΩ resistors.



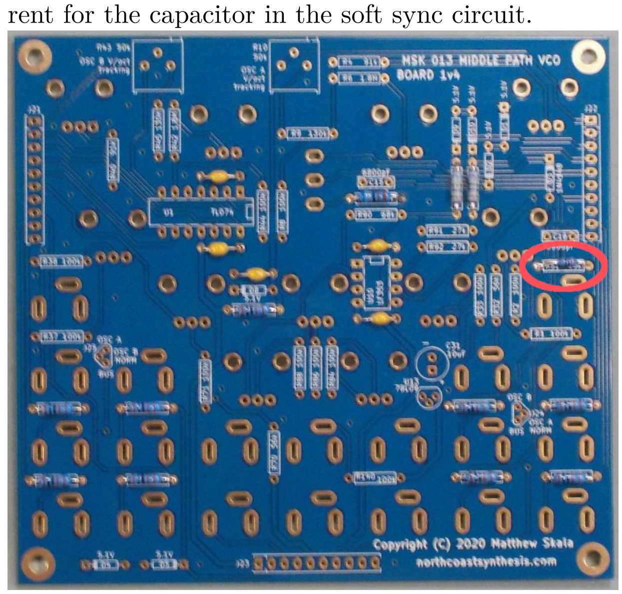
Install the nine 1kΩ (brown-black-black-brown) resistors R20, R23, R31, R36, R58, R61, R69, R74, and R83. Most of these are for limiting current and ensuring stability on op amps that drive output jacks. R83 is a ballast resistor for the −5V reference supply regulator. Do not confuse these with other power-often values, such as 10kΩ and 100kΩ.



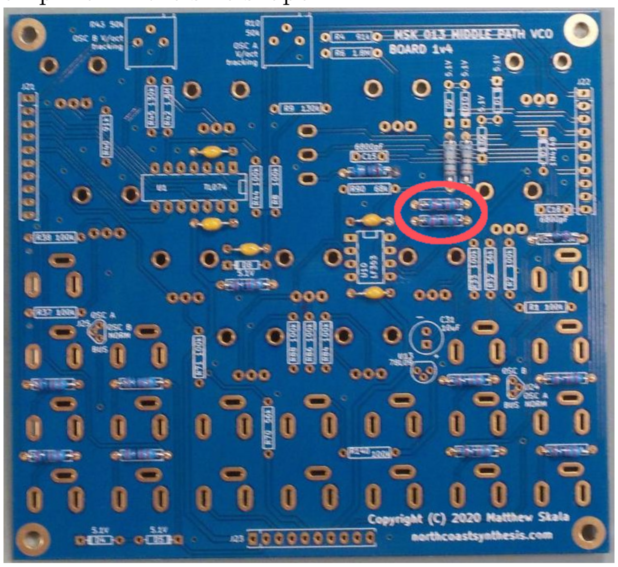
Install the single 6.8kΩ (blue-grey-black-brown) resistor R50. This resistor couples sync pulses from the master to the slave oscillator in “firm” sync mode. Do not confuse it with the 68kΩ resistor.



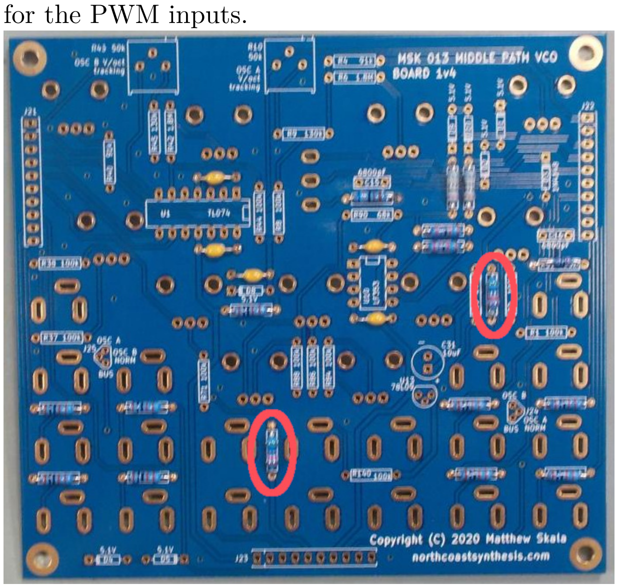
Install the single 10kΩ (brown-black-black-red) resistor R51. This resistor provides recharging current for the capacitor in the soft sync circuit.



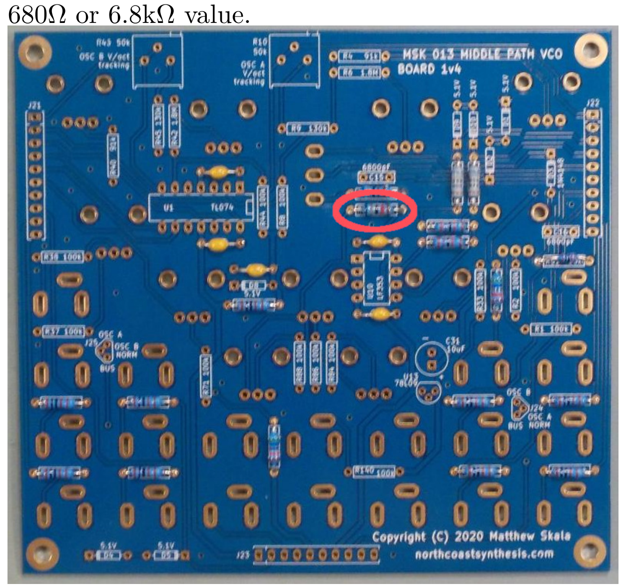
Install the two 27kΩ (red-violet-black-red) resistors R91 and R92. These set gain for an inverting amplifier in the sine shaper.



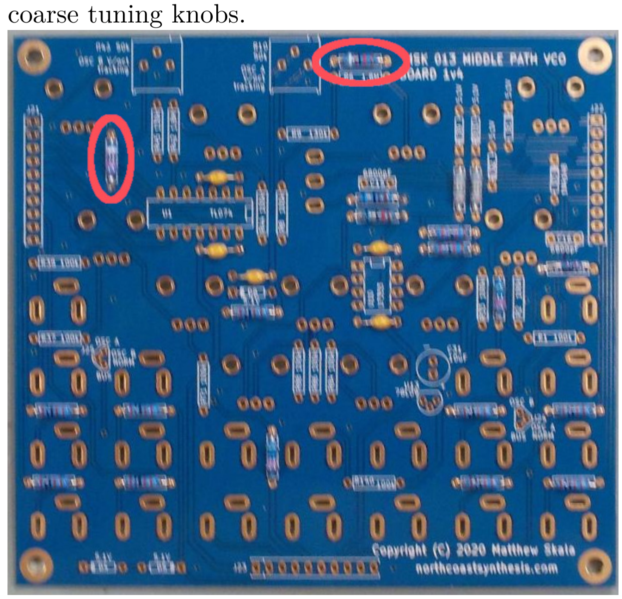
Install the two 56kΩ (green-blue-black-red) resistors R32 and R70. These set the normalling voltage for the PWM inputs.



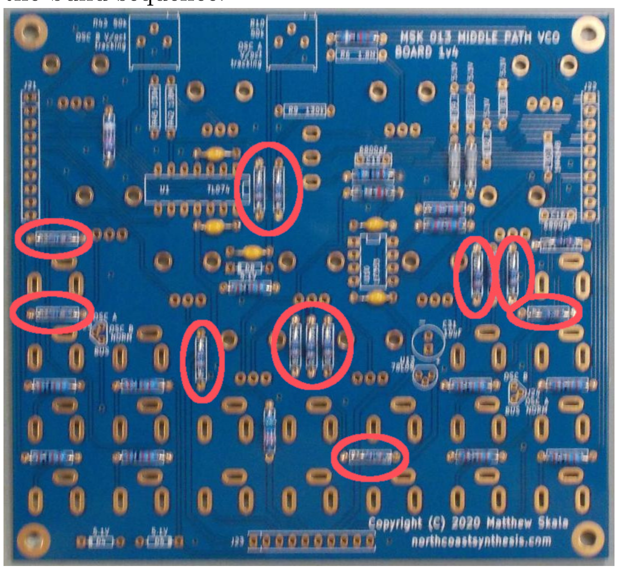
Install the single 68kΩ (blue-grey-black-red) resistor R90. This resistor sets the gain for the mixing amplifier in the sine shaper. It is the last resistor in the build with a "68" code, but double check that this resistor really is 68kΩ and not the similarly-coded 680Ω or 6.8kΩ value.



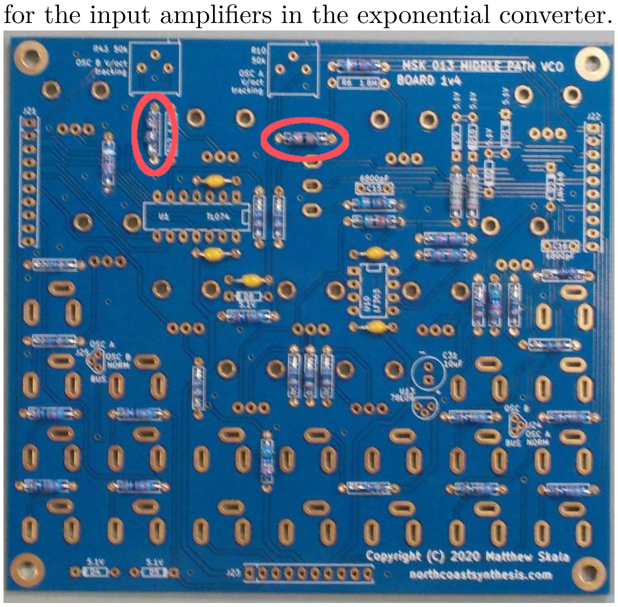
Install the two 91kΩ (white-brown-black-red) resistors R4 and R40. These set the scale factor for the coarse tuning knobs.



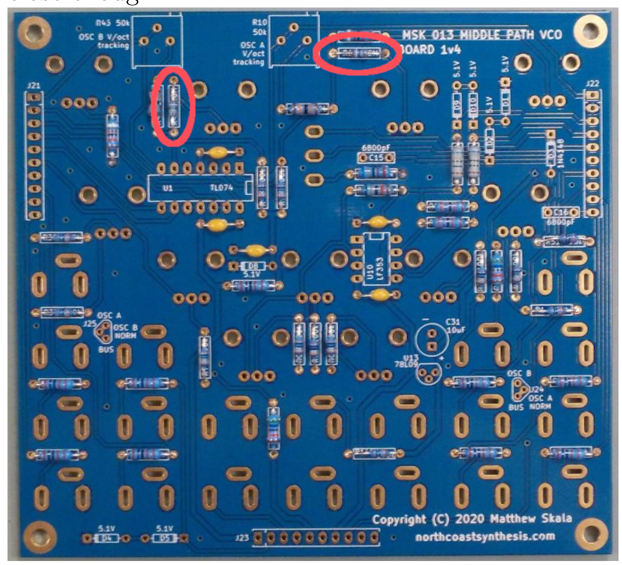
Install the twelve 100kΩ (brown-black-black-orange) resistors R1, R2, R8, R33, R37, R38, R44, R71, R84, R86, R88, and R140. Most of these are used to set input impedances in op amps that take input from the outside world. R4 and R44 set the offset for the exponential converters, effectively the frequency at 0V control input; and R140 sets the normalling voltage for the sine shaper's middle input. These are the last power-of-ten fixed resistors in the build sequence.



Install the two 130kΩ (brown-orange-black-orange) resistors R4 and R45. These resistors, along with the trimmers to be installed later, set the gain for the input amplifiers in the exponential converter.



Install the two 1.8MΩ resistors (brown-grey-black-yellow) resistors R6 and R42. These set the scale factor for the fine tuning knobs. It is possible that some kits may ship with resistors coded 1.82MΩ (brown-grey-red-yellow) instead of 1.80MΩ. Either is close enough.



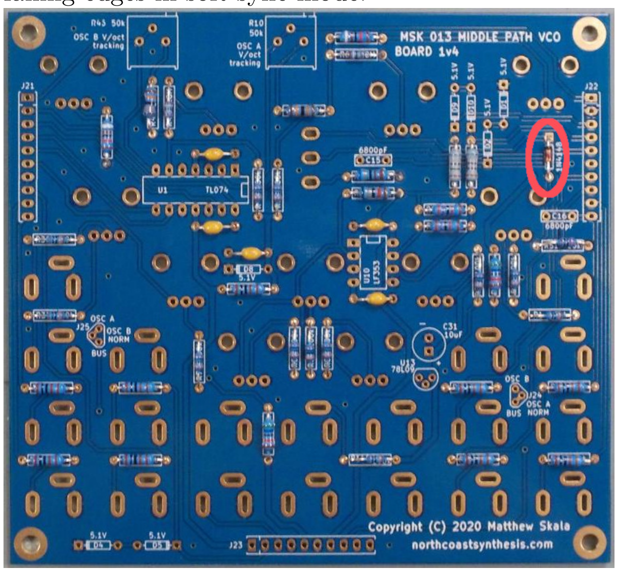
Semiconductors

There are two different kinds of diodes to install on this board and they look almost exactly alike: one 1N4148 or 1N914 switching diode named D3, and seven 1N5231B or equivalent 5.1V Zener diodes named D1, D2, D4, D5, and D8–D10. All three diodes will be packaged in little pink glass beads with near-microscopic etched numbers indicating their type. Be careful not to confuse them; swapping the switching diode with a Zener will result in incorrect behaviour of the full-wave rectifier at high input voltages, and incorrect feedback levels probably causing either very strong oscillation at all resonance settings, or preventing oscillation entirely.

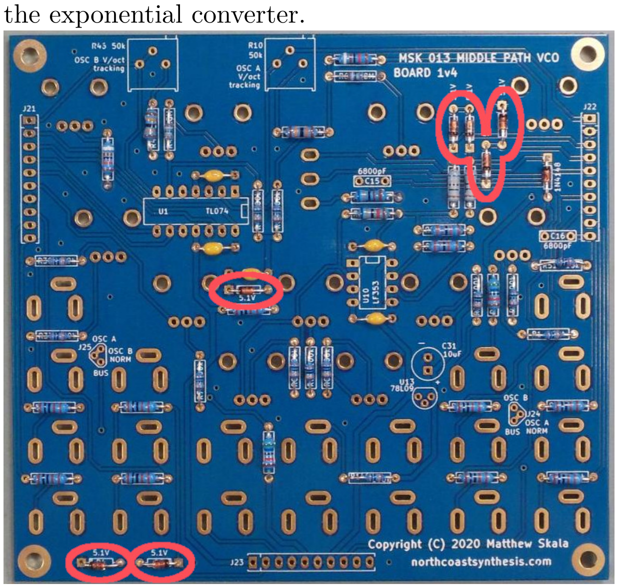
If you are unsure which diode is which and you cannot confidently read the etched markings, hook up a diode in series with a 10kΩ resistor reverse-biased across a 12V power supply and measure the voltage drop across the diode. If it is near 12V, then you are testing the switching diode; if it is near 5.1V, you are testing one of the Zener diodes; if it is near 0.6V, you probably have the diode connected forward-biased and should reverse it or the power supply.

Both kinds of diodes are polarized and must be installed in the correct direction to function properly. One end of the glass body of the diode package will be labelled with a black band or stripe; that end is the *cathode*. The direction for the cathode is marked on the PCB silkscreen by a matching stripe in the printed symbol; and the solder pad for the cathode is square rather than round. There are also labels saying “5.1V” and “1N4148” next to the diode footprints as additional clues to which diode goes where.

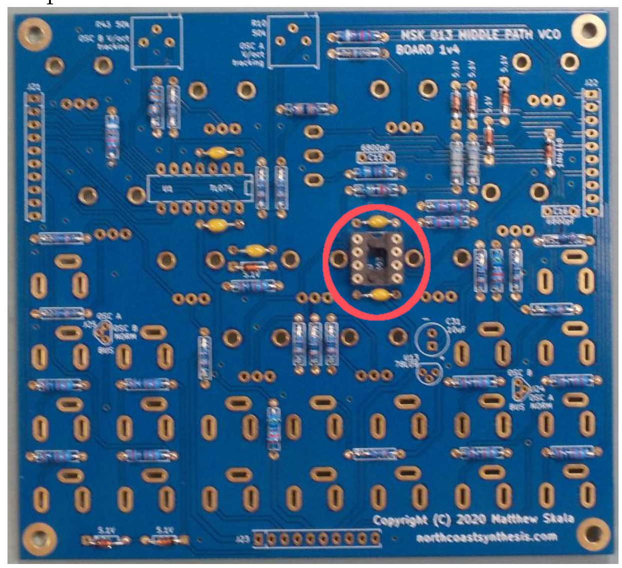
Install the switching diode D3, bearing in mind the notes above. This diode separates the rising and falling edges in soft sync mode.



Install the seven 5.1V Zener diodes D1, D2, D4, D5, and D8–D10. Most of these are used in pairs to clip signal voltages, in the pulse and sine shapers. D8 is used to regulate a negative voltage offset for the exponential converter.



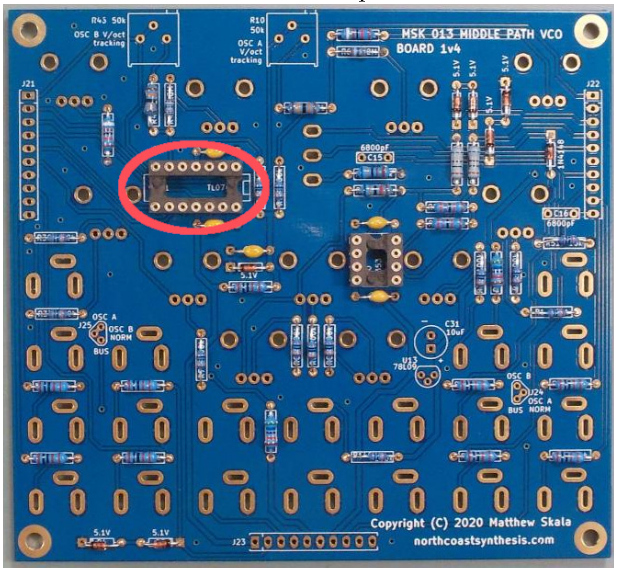
Install the 8-pin DIP socket for the LF353 dual operational amplifier U10. The amplifiers in this chip drive the two ends of the resistor chain for the sine shaper.



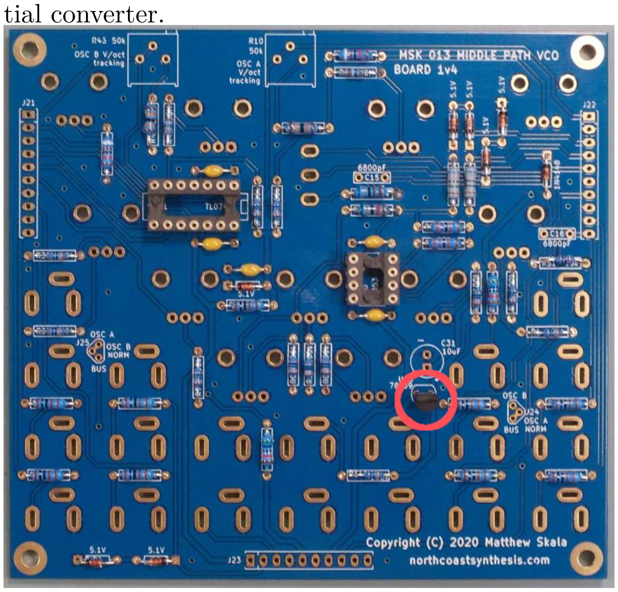
Recall from the Board 2 build that DIP sockets themselves do not care which direction you install them, but it is critically important that the chip installed in the socket should be installed in the right direction. To help with that, the socket will probably be marked with notches at one end (indicating the end where Pin 1 and Pin 8, or Pin 14 as applicable, are located) and you should install the socket so that the notched end matches the notch shown on the PCB silkscreen. The solder pad for Pin 1 is also distinguished by being rectangular instead of rounded.

Installing DIP sockets without having them tilted at a funny angle can be tricky. I recommend inserting the socket in the board, taping it in place on the component side with vinyl electrical tape or sticking it there with a small blob of putty at each end, then soldering one pin on one corner and checking that the socket is snug against the board before soldering the other pins. That way, if you accidentally solder the first pin with the socket tilted, it will be easier to correct (only one pin to desolder instead of all of them).

Install the 14-pin DIP socket for the TL074 quad operational amplifier U1. The amplifiers in this chip process pitch control voltages and drive the reference current sources for the dual exponential converter.



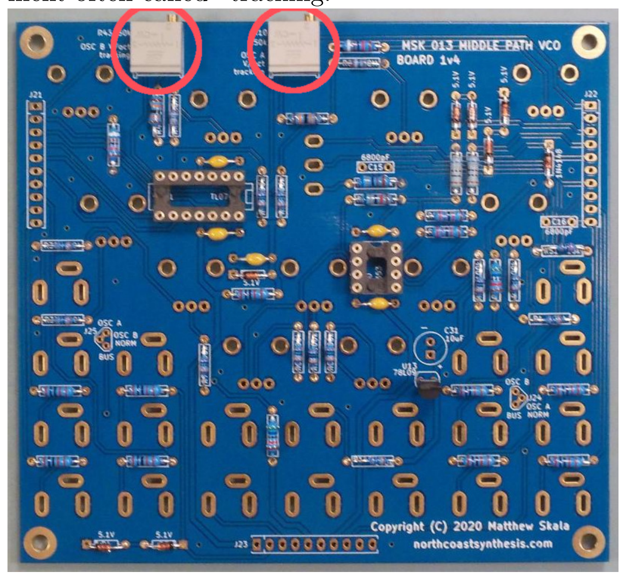
Install the 78L09 regulator U13. See page 22 in the Board 2 instructions for general comments on how to install TO-92 components like this one. This regulator provides a +9V reference used in the exponential converter.



Trimmer potentiometers

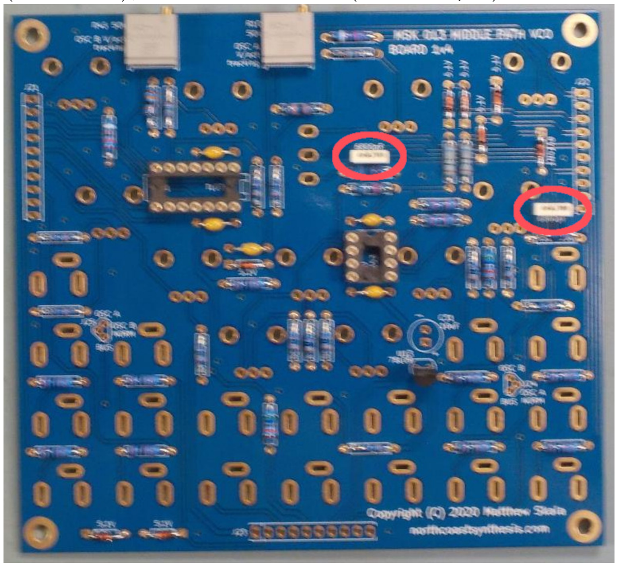
Trimmers are not exactly polarized, but the three legs of each trimmer serve different functions and need to be connected to the right holes. The physical arrangement of the legs and corresponding holes should make it impossible to install the trimmers wrong way round.

Install the two 50kΩ multiturn trimmers R10 and R46. These trimmers set the scale factor for the V/octave pitch CVs of the two oscillators, an adjustment often called "tracking."

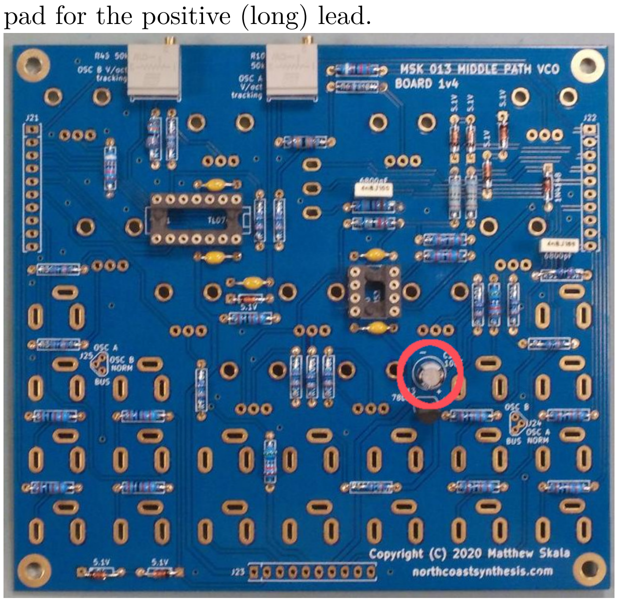


More capacitors

Install the two 6800pF film capacitors C15 and C16. These are coupling capacitors used in the sync circuit. They are unpolarized and may be installed in either direction. The markings on film capacitors vary depending on the manufacturer and model. These ones might be marked "682" (for 68 followed by two 0s number of picofarads, like the resistor code), "6n8" (for 6.8nF), or even “0.0068” (value in μF).



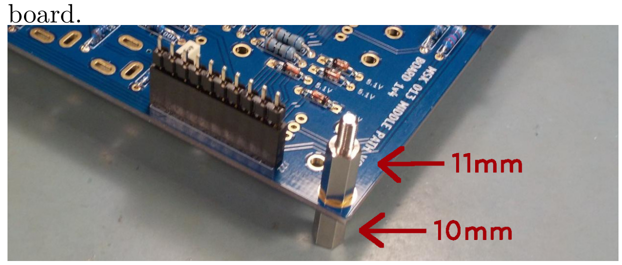
Install the 10μF electrolytic capacitor C31. This filters the +9V reference voltage. It is a polarized component and may explode if installed backwards. It will be marked on its casing with a stripe and minus signs to indicate the negative lead; the positive lead will probably also be longer. These clues should be matched with the markings on the PCB: plus and minus symbols in the silkscreen and a square solder pad for the positive (long) lead.



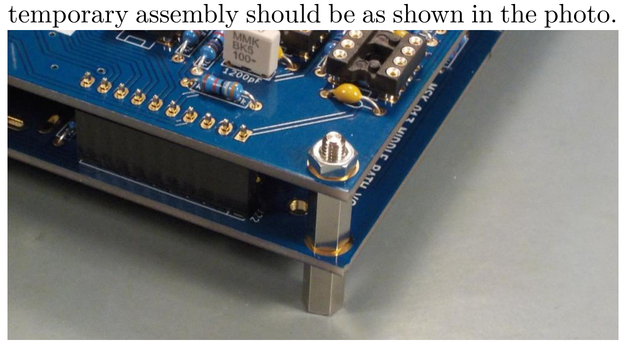
Board to board connectors

Fasten the four 10mm standoffs on the back of Board 1; that is the side opposite the components already installed. The male ends of the 10mm standoffs should pass through the mounting holes in the board and mate with the female ends of the 11mm standoffs on the front or component side of the board. Be careful to get right which standoffs are the shorter ones (10mm) and which are the longer ones (11mm).

Mate the three pairs of 10×1 header connectors J21–J23 and P2–P4 and place them (do not solder yet) in the J21–J23 footprints on Board 1 with the legs of the female connectors going through the board.



Place your completed Board 2 from the previous chapter on top of the assembly, component side up with the legs of P2–P4 going through the footprints on the back of the board, and fasten the board to the 11mm standoffs with the four hex nuts. The resulting temporary assembly should be as shown in the photo.



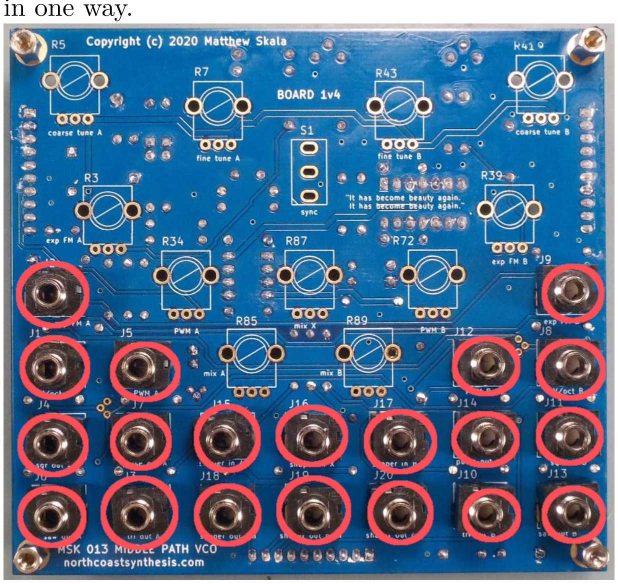
Solder J21–J23 and P2–P4 in place on the two boards. Then remove Board 2 and the hex nuts holding it in place, but keep the standoffs attached to Board 1.

Panel components

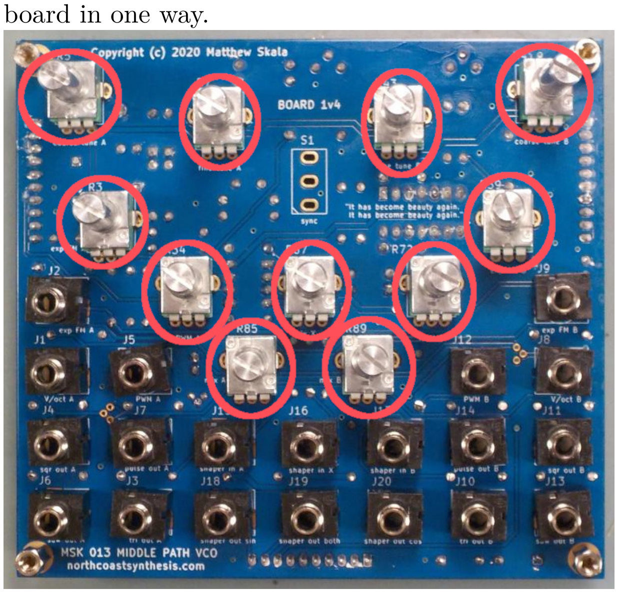
Flip Board 1 over; you will now be installing the components that go between it and the panel. The pieces fit together in a straightforward way, but see the exploded assembly diagram on page 66 if further clarification is needed.

Remove any hardware such as nuts and washers that may be supplied pre-threaded onto the panel components and set all that stuff aside before proceeding.

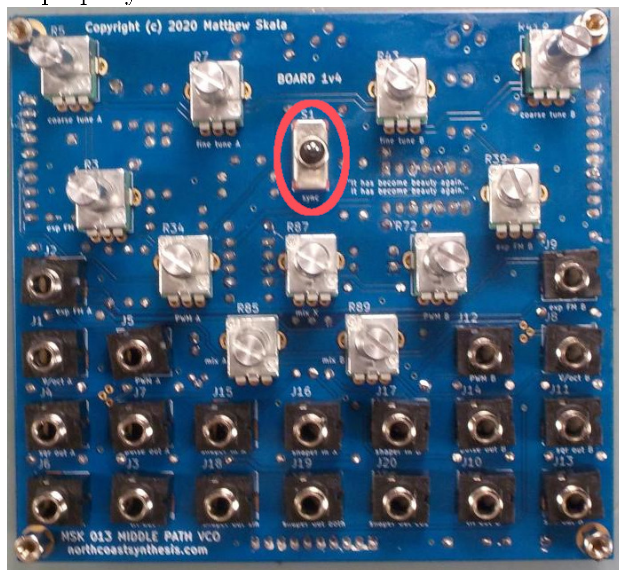
Place (do not solder yet) the twenty phone jack sockets J1–J20 in their footprints. These are for patching signals to and from other modules. These components should only be able to fit into the board in one way.



Place (do not solder yet) the eleven panel control potentiometers R3, R5, R7, R34, R39, R41, R43, R72, R85, R87, and R89 in their footprints. These components, too, should only be able to fit into the board in one way.



Place (do not solder yet) the toggle switch S1 in its footprint. This switch is used to select the sync mode. The electrical connections on this switch are symmetrical, but there is a keyway or groove on the threaded bushing of the switch, and the keyway must be oriented downward for the mounting hardware to fit properly later.



Line up the panel on top of the assembly. Fasten it in place by driving the four machine screws through their corresponding holes into the 10mm standoffs.

Install all the hardware for the panel components. The potentiometers will each have one washer and one hex nut; the washer goes on first, nearest the panel. In the case of the jack sockets, the knurled nuts provided for these will have screwdriver slots on one side, and those should face the outside with the smoother side facing the panel. The switch should have a locking ring with a little tooth that fits into a hole just below the bushing; this will only work properly if you put the switch into the board in the correct orientation. The locking ring goes closest to the panel, followed by a toothed lockwasher and two nuts. The sharper points on the lockwasher should point out, facing the nut, if one side feels sharper than the other.

Do not overtighten any of this hardware, and be careful, if you are using wrenches or pliers, to avoid scratching the panel. Wrapping the tool jaws with tape may help.

Final assembly

Insert the LF353 chip U10 in its socket on Board 1. Be careful to insert it right way round: the end with Pin 1 will be marked by an indentation at one corner or a notch in the end and this end of the chip should be inserted to match the notch in the socket and on the board silkscreen and the rectangular Pin 1 solder pad. The Pin 1 end of the chip is at the bottom when the module is inserted in a rack.

Also be careful that all the legs of the chip go into the corresponding holes in the socket. These chips, when brand new, usually have their legs splayed outward a little bit (a measure intended to help them fit snugly into circuit boards when used without a socket) and you must gently bend the legs inward in order to fit them in the sockets. If you apply pressure to a chip prematurely, without all the legs properly fitting into the holes, it is easy to have the legs fold up or even break off.

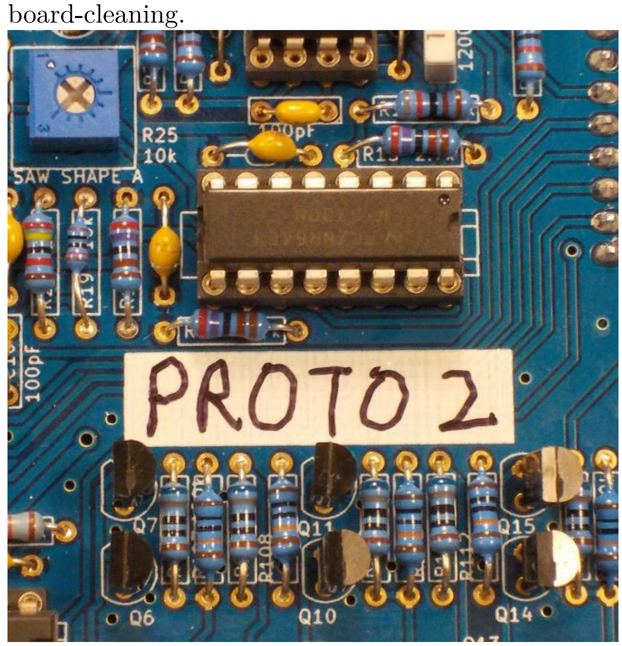
Similarly, insert the TL074 chip U1 in its socket on Board 1. The same general comments on installing DIP chips apply here.

It should not be necessary to remove the panel from Board 1 again. Just attach Board 2, carefully fitting its header plugs into the header sockets on Board 1 and the male ends of the standoffs through the corresponding holes in Board 2. Then use the hex nuts to fasten Board 2 in place.

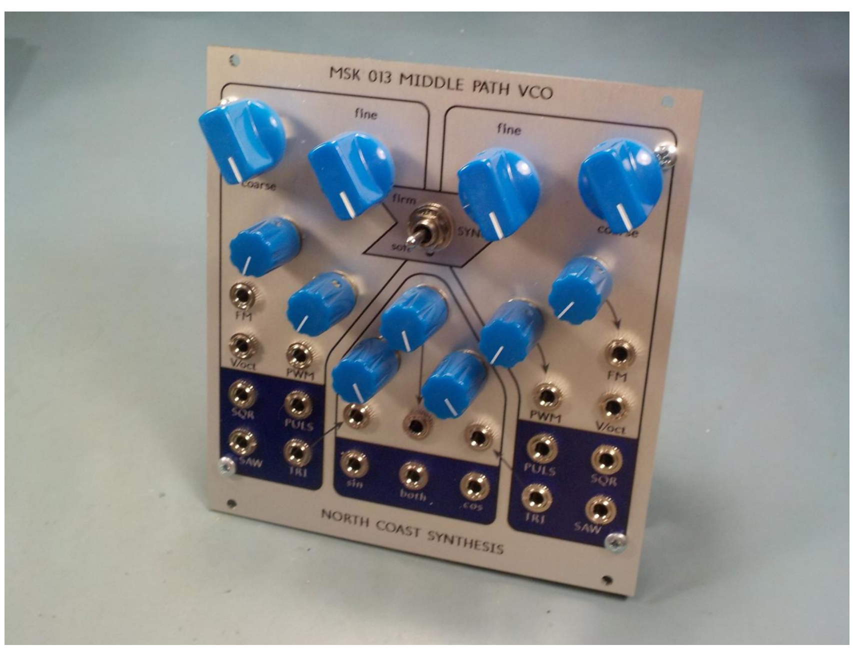
Insert the LF353, TL074, LM13700, THAT320, and AD633 chips in their sockets on Board 2. Be careful to insert them right way round, with the Pin 1 markings on the chips matching those on the board. As with the chips on Board 1, be careful all the legs are in the holes of the socket before you press each chip down, lest you fold up the delicate legs. Also be careful not to confuse which chip goes in which socket; and be especially careful with the THAT320 and AD633 chips. They are expensive.

Add the knobs. Be careful not to overtighten the setscrews; they have a tendency to strip.

There is a rectangular white area on Board 2, just above the sine shaper, reserved for adding a serial number, signature, quality control marking, or similar. Use a fine-tipped permanent marker to write whatever you want there. Isopropyl alcohol will probably dissolve marker ink, so do this step after any board-cleaning.



Your module is complete.



Adjustment and testing

Most features of the Middle Path VCO should work to an acceptable standard without requiring any adjustment; but the scale factor for the V/octave inputs (also known as "tracking") and the shape of the sawtooth waveform outputs each benefit from adjustment of the built-in trimmers as described in this section. I also give some suggestions on troubleshooting build problems.

A multimeter is recommended for basic debugging. An oscilloscope and an accurate source of voltages are recommended for tracking and wave shape adjustments.

Short-circuit test

With no power applied to the module, check for short circuits between the three power connections on the Board 2 Eurorack power connector. The first pair of pins at the right, marked with white on the circuit board, are for −12V. The next three pairs are for 0V; and the next pair after that are for +12V. Check between each combination of these three voltages, in both directions (six tests in all). Ideally, you should use a multimeter's "diode test" range for this; if yours has no such range, use a low resistance-measuring setting. It should read infinite in the reverse direction (positive lead to −12V and negative lead to each of the other two, as well as positive lead to ground and negative to +12V) and greater than 1V or 1kΩ in the forward direction (reverse those three tests). If any of these six measurements is less than 1kΩ or 1V, then something is wrong with the build, most likely a blob of solder shorting between two connections, and you should troubleshoot that before applying power.

Optional: Although we test all cables before we sell them, bad cables have been known to exist, so it might be worth plugging the Eurorack power cable into the module and repeating these continuity tests across the cable's corresponding contacts (using bits of narrow-guage wire to get into the contacts on the cable if necessary) to make sure there are no shorts in the cable crimping. Doing this *with the cable connected to the module* makes it easier to avoid mistakes, because the module itself will short together all wires that carry equal potential, making it easier to be sure of testing the relevant adjacent-wire pairs in the cable.

Plug the module into a Eurorack power supply and make sure neither it nor the power supply emits smoke, overheats, makes any unusual noises, or smells bad. If any of those things happen, turn off the power immediately, and troubleshoot the problem before proceeding.

Checking and adjusting wave shapes

Apply power to the module and remove any other cables. Set all the tuning knobs and PWM knobs to the centres of their ranges, and set the sync switch to the centre "off" position. Use an oscilloscope to examine each of the four output waveforms from the master oscillator and compare them with the examples in Figure 3.

They should all look similar to the examples. The exact frequency may be different. Try turning the master oscillator PWM knob and see that it varies the duty cycle of the PULS waveform.

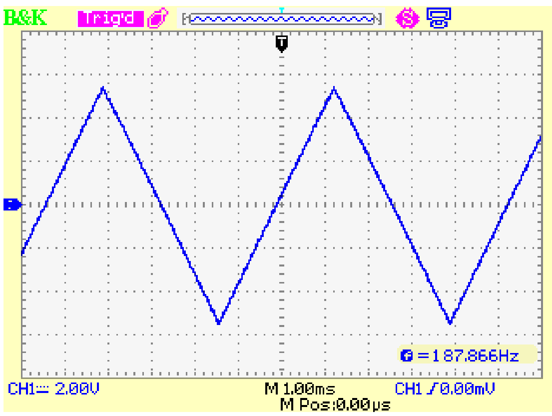
If the module is not already adjusted, the SAW waveform will probably have a glitch or kink in it where it crosses zero, as shown in the figure. Adjust the SAW SHAPE A trimmer, which is on the back of the module in the upper right quadrant of the board, to minimize this kink. There will probably always be a small ultrasonic spike in the waveform at this point, but you should be able to get the straight segments on either side to align well with each other.

Repeat these checks for the slave oscillator, and adjust the SAW SHAPE B trimmer, at the centre left of the board, to make the slave SAW shape as good as possible.

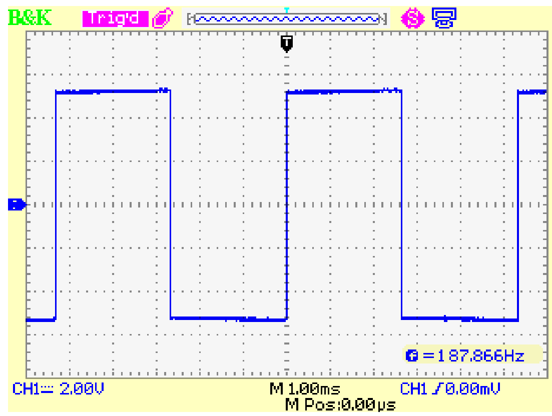
Checking the sine shaper

This test is not absolutely necessary, but it provides an easy way of checking the operation of the sine shaper. It will require an oscilloscope capable of X–Y display mode.

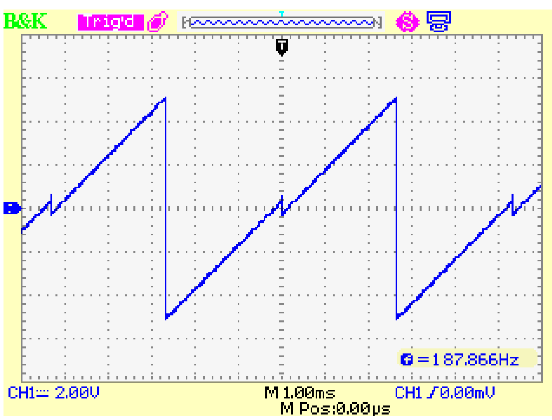
Turn the coarse and fine tuning knobs for one of the oscillators to about 1 o'clock, that is, a lit-



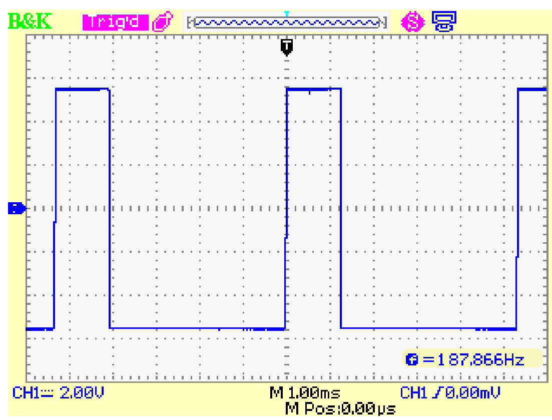
TRI



SQR

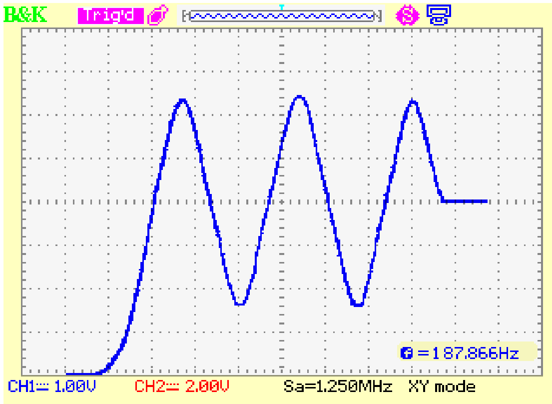


SAW

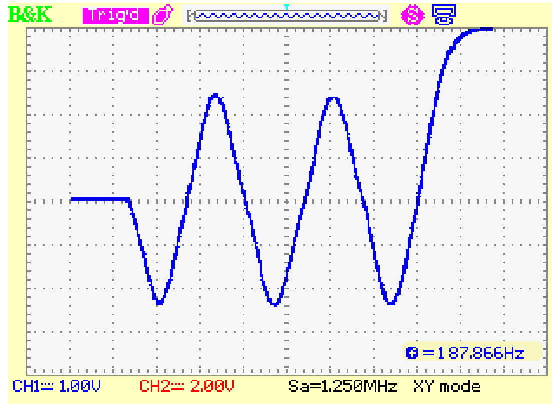


PULS

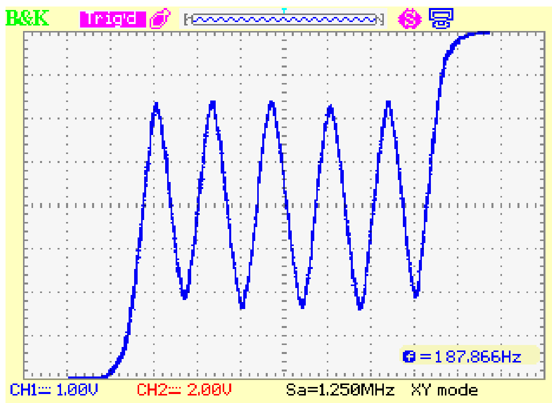
Figure 3: Output waveforms.



sin



cos



both

Figure 4: Sine shaper voltage functions.

tle higher than midpoint. Turn off sync. Turn the shaper knob for that oscillator to maximum (fully clockwise) and the other two shaper knobs to zero (fully counterclockwise). Use the TRI output for the oscillator as the horizontal input (X coordinate) for your oscilloscope and connect each of the three sine shaper outputs to the vertical, in turn. Compare the display with the examples in Figure 4.

In this test setup, the oscilloscope display represents the voltage function computed by the shaper. Each result should look a lot like the examples; there may be some small variation in the height or spacing of the peaks. If there is a significant difference from the examples, such as a peak much higher or lower than the others or missing entirely, it suggests a problem in the shaper, most likely with one of the transistors; see the "Troubleshooting" section below.

Tracking (with automated test)

"Tracking" refers to the slope of the V/octave control voltage response. It should be exactly 1.0V/octave. The trimmers R10 and R46, located on Board 1, adjust this response for the master and slave oscillators respectively.

The best way to adjust this setting, if you have the equipment and skills, is by hooking up the module to a computer that can send it control voltages, measure the output frequency in self-oscillation, and compute an estimate of the current V/octave ratio, which allows realtime feedback as you adjust the trimmer. I provide a piece of software in the file `voct-0.1.tar.gz` to support this process.

The software is written for the Linux ALSA MIDI and PCM drivers, and it includes hardcoded assumptions about things like device numbers. *You need C programming skills to use this software. I will not* *provide support on it.* If you cannot modify the software as needed to suit your installation, then I recommend using the manual tracking procedure in the next section instead.

Read the C source code and make any appropriate changes for your installation. Compile it. Connect your MIDI-to-CV interface to the V/oct input on one oscillator of the MSK 013, and connect the SQR output to your computer's audio input (with attenuation, if required). Remove any other patch cables from the MSK 007. Optionally (requires other appropriate software, not included), send MIDI note 69 to the MIDI interface and adjust the tuning of the MSK 013 to make it oscillate at 440Hz; otherwise set the coarse tuning to about 10 o'clock and the fine to its midpoint. Adjut the sensitivity of the audio input, or the attenutation if you are using an attenuator, to bring the Leapfrog's signal to about 50% of full scale. Run the `vcoslope` software.

The vcoslope program sends random MIDI notes, makes brief recordings of the oscillator output, and attempts to fit an exponential function (using linear regression) to the note/frequency data in the last N notes, for several different values of N. From that it can determine the current sensitivity of the V/octave input. Using multiple frequencies to test like this gives better accuracy than would be the attainable with just testing at two frequencies (as in the standard manual procedure). Using notes in random order is preferable to testing them in an increasing or decreasing sequence, because of self-heating effects in the exponential converter. The program tries multiple sample sizes (the most recent 10, 32, 100, and 316 points) to allow both quick feedback on any trim changes, and accurate results over longer periods.

It will start producing lines of output, one every few seconds. Each line starts with a decimal sequence number (1, 2, 3, . . .) and the MIDI note number that was sent. The next two columns are the measured frequency in Hertz, and the number of octaves plus or minus that is relative to the 440Hz reference pitch. Then come up to four columns of V/octave estimates: the first determined from the last 10 notes tested, the second from the last 32 notes, then 100 notes, then 316 notes. These columns each show up only once there have been the requisite number of notes, so at first there will be no such column, then the first one will appear on the tenth note, then the second at note 32, and so on.

Let the program run for at least 10 or 20 notes so you can get some idea of the module's current V/octave response. Then try adjusting the trimmer one turn clockwise. Watch for another 10 lines of output. The 10-note V/oct estimate should start to move, then settle in on a new value. From there you should be able to estimate how far (how many turns) and in which direction you need to adjust the trimmer to bring the response to 1.000V/oct. Try to do that. As you get in closer, the natural noise in the V/oct numbers may become significant in relation to the sizes of adjustment you are making. In that case, switch to one of the slower-updating columns to get a more stable reading (larger sample size). You will need to wait longer between adjustments for those columns to reach full precision. Continue until you have the module performing as accurately as you want, or until you run out of patience.

Repeat the process for both oscillators. When adjusting the slave, make sure sync is turned off.

Tracking (by hand)

This simpler tracking procedure does not require computer skills, only the ability to send reproducible control voltages of 0V and 1V to the module and test the resulting frequencies. It is somewhat less accurate because it tests only two frequencies instead of averaging over many, but most DIY VCOs are routinely adjusted this way.

A North Coast Synthesis MSK 008 Octave Switch, assuming it has itself been properly adjusted, makes an ideal voltage source for the following procedure.

Hook up your control voltage source to the oscillator's V/oct input, set up your equipment as necessary to test the frequency of one oscillator output, disconnect any modulation signals, and power up the module.

Send a 0V control voltage to the oscillator. Tune it with the coarse and fine tuning knobs to an oscillation frequency of 220Hz (or any arbitrary frequency of your choice, but this one is convenient).

Without changing the tuning knob settings, send a 1V control voltage to the oscillator. Adjust the trimmer, not the tuning knobs, to bring the oscillation frequency to 440Hz (or twice the initial frequency if you are using something other than 220Hz).

Send a 0V control voltage and test the output frequency; is it 220Hz or your chosen other reference frequency? If not, adjust the tuning knobs to make it so. Repeat these two steps, of alternately adjusting for the low frequency with 0V and the tuning knobs, and the high frequency with 1V and the trimmer potentiometer, until both readings are reliably what they should be without seeming to need further adjustment.

For even better accuracy: use two control voltages more than 1V apart, and a correspondingly wider frequency range. For instance, an MSK 008 Octave Switch can conveniently generate +1V and −1V, which could be used with reference frequencies of 440Hz and 110Hz to set tracking over two octaves instead of just one.

Troubleshooting

If the module does not perform as it should, some kind of debugging or troubleshooting may be necessary. It would require several books to convey all the skills and knowledge useful in troubleshooting even a simple electronic circuit like this one, but here are some possible symptoms and some suggestions on diagnosis and treatment.

In general, the first order of business in debugging is to narrow down the set of things that could be wrong. Think about the different sections of the module: master oscillator, slave oscillator, sine shaper, sync, power system. Any single problem is likely to involve at most one of those, although it is also possible for there to be more than one independent problem occurring at once. If you can determine which of those large sections is at fault, try to narrow it down further: does the problem affect just one output? Just one input? Is it limited to a specific feature of the module? The more narrow a description you can find, the fewer places you will have to look to find out what is wrong.

No response from the module at all: This module should produce some output from each oscillator's TRI, SQR, and SAW jacks (at least) at all times regardless of the knob and switch settings, so if there is no such output it suggests a power problem, such as a power cable plugged in wrong or a short circuit. This might even be a problem in the power supply and not the module itself. If possible, check the power supply with some other load instead of the new module to rule out the power supply itself as the location of the problem.

General quality issues: many problems can be diagnosed just by looking closely at your work, preferably with at least one night's sleep between when you assembled the module and when you examine it. Look for bad solder joints that fail to connect; solder bridges between nearby connections (especially on the discrete transistors in the sine shaper); components missing; components exchanged (especially resistors with similar colour codes, such as 1kΩ swapped with 10kΩ); polarized components such as diodes mounted backwards; and so on.

General tips for debugging DIP ICs: make sure for, for each IC, that

- it really is the type of IC it's supposed to be, not something else (beware of cheap ICs you buy from Chinese sellers on eBay and AliExpress, especially if they are offering unusually good prices on expensive chips like the AD633);
- it is plugged in snugly;
- all the legs of the chip go nicely into the corresponding holes in the socket, with none bent outside or folded up under the chip;
- it is plugged in *at all* (forgetting to do so is a surprisingly common mistake!);
- it is plugged in the right way around, with the Pin 1 indentation or notch matching the clues on the board (if this is wrong, the chip is probably destroyed and will need to be replaced);
- there are no solder bridges on the chip socket, unsoldered pins, debris clogging the socket holes, or similar; and
- its decoupling capacitors (the small ceramic ones) are installed and there is nothing wrong with their solder joints.

You can try swapping a suspect chip with another one of the same type from elsewhere in the module and see if that causes the problem to change; if so, it's likely one of the two you swapped was bad.

No signal coming out of one jack, or no response to input on one jack: make sure that a signal or a response is expected based on the other settings of the module, but if so, this suggests a bad jack. During prototyping I had some problems with jacks that had been overenthusiastically soldered, warping their plastic bodies so that they shorted out when receiving plugs. If possible, try wiggling the plug in the jack, and try inserting it and removing it slowly, watching the response. If it works with the plug inserted just partially, but not when fully inserted, that suggests a damaged jack.

Bad wave shapes: Each oscillator output comes from the core and passes through at least a little bit of circuitry unique to that output. If the problem shows up in just one waveform, it is probably in the amplifier or shaper for that one output. If it affects multiple outputs, it's more likely a problem with the cores. Consult the schematic to figure out which ICs are relevant to the problem you're seeing, and check those ones first. One syndrome I've noticed is that a bad MOSFET in the sawtooth shaper (which could be defective to begin with; damaged by static or by soldering heat; or subjected to a solder bridge) tends to lead to a slanted-topped square wave instead of a sawtooth on the SAW output.

Exponential converter troubles: some parts of the exponential converter are shared between the two oscillators, so if there are serious problems with tracking or modulation affecting *both* oscillators, it points to an issue with those shared components (the THAT320 and reference current generators). On the other hand, an issue with the tracking or modulation affecting only one of the two oscillators is likely to be in the parts specific to that one oscillator.

Sine shaper problems: one of the most common build issues with this module is for a transistor in the sine shaper to be badly soldered, causing it to either conduct when it shouldn't, or fail to conduct when it should. Since each of these transistors is meant to turn on at a different input voltage, it's possible to locate which transistor is bad by figuring out at which voltage the problem shows up. Each positive and negative peak in the voltage curves corresponds to one transistor. If you measure the voltage curves (as described under "Checking the sine shaper" above) and they do not match the examples, consult the idealized curves in Figures 5 and 6, in which each peak is labelled with the name of the transistor responsible for it. Half the transistors contribute to each of the "sin" and "cos" outputs, and all transistors contribute to the "both" output. The transistor named at whatever part of the curves seems not to match the examples, is the one you should check first as a possible source of the trouble.

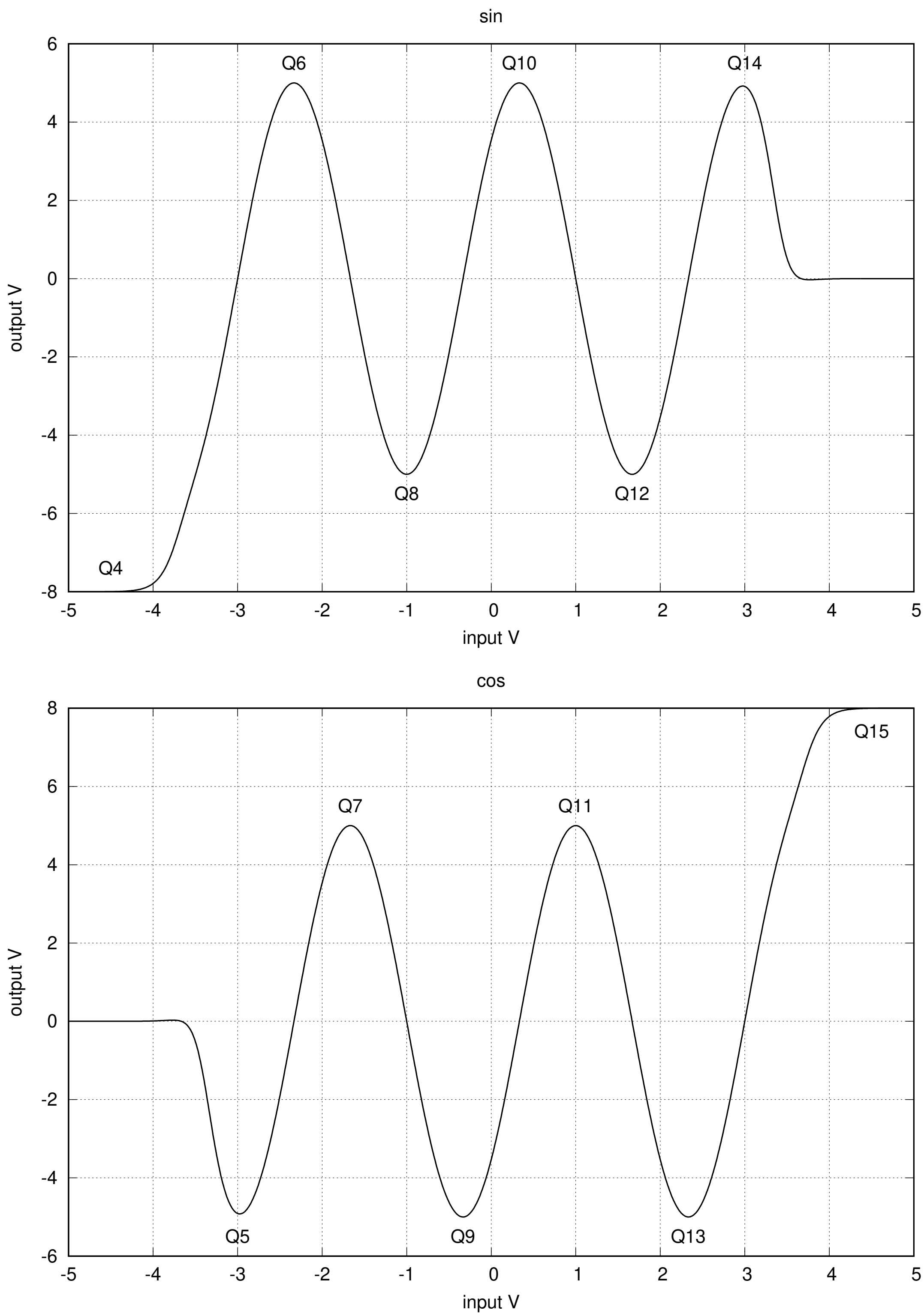


Figure 5: Voltage functions for “sin” and “cos” outputs.

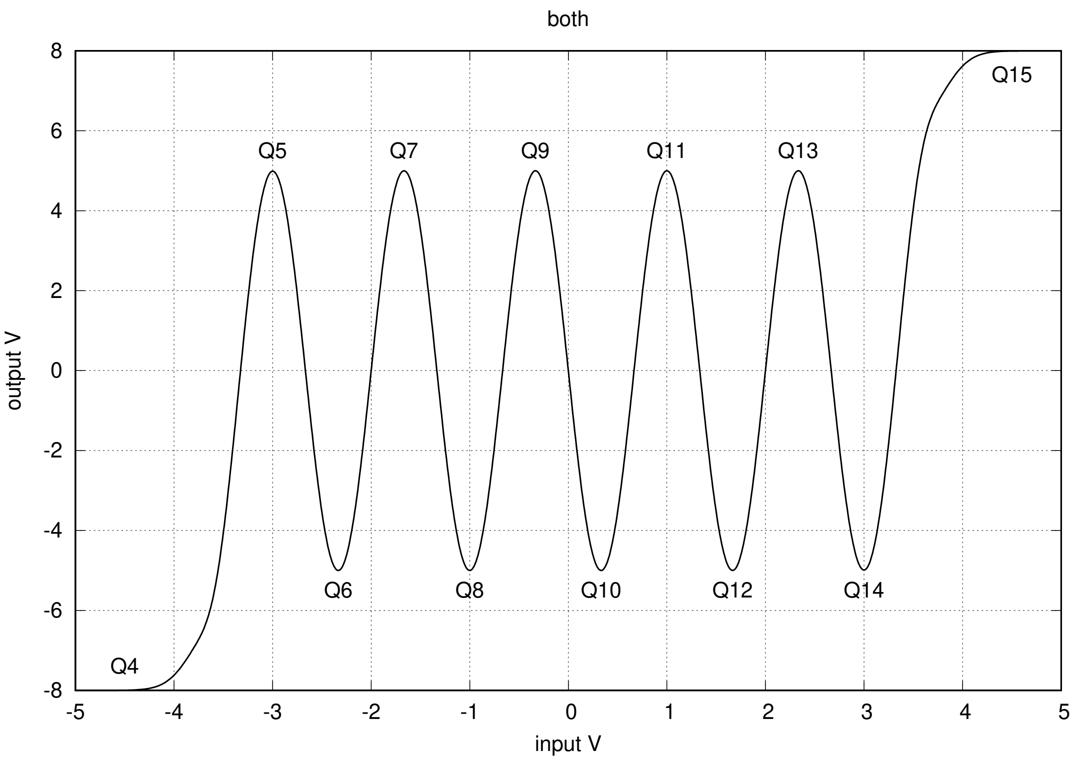
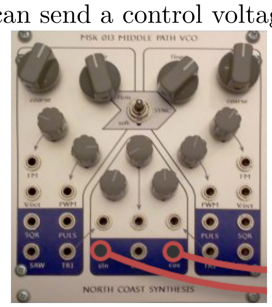


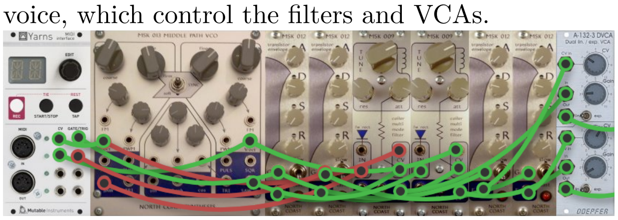
Figure 6: Voltage function for “both” output.

Patch ideas

The simplest way to patch the Middle Path is to not really patch it at all. Just running it by itself with no input except the front-panel controls, it can produce a variety of different spectra for drones and background pads. Taking output from the "sin" and "cos" outputs of the sine shaper gives a fake stereo effect. Note that the V/octave inputs normalize to the Eurorack CV bus when there are no cables plugged into the front panel, so even without plugging in an input cable, the module can take pitch control from somewhere else if used with modules like the Doepfer A-185-1 that can send a control voltage to the bus.

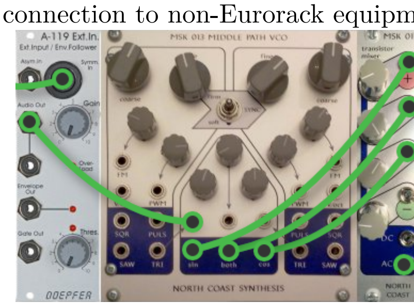


Here are two independent subtractive East Coast-style voices in an 84HP Eurorack row, using the Middle Path as a dual general-purpose VCO. Pitch CV from the MIDI interface drives the two V/oct inputs of the Middle Path, as well as the pitch CV inputs of the filters, which in this case are Coiler VCFs. Gate CV drives two ADSR envelope generators for each voice, which control the filters and VCAs.



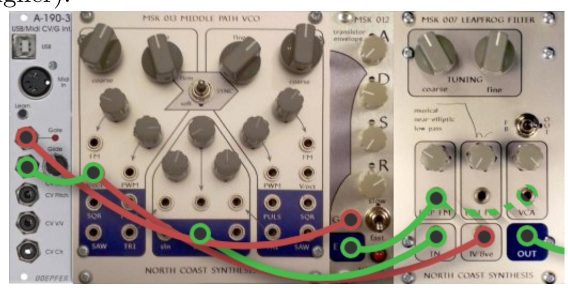
A more full-featured subtractive patch can use both oscillators of the Middle Path in a single voice, as well as showcasing a couple of other North Coast modules. Pitch CV goes through a Dual Octave Switch, which allows for easily shifting either oscillator up or down during performance. The Fixed Sine Bank provides PWM to one oscillator and FM to the other. The PWM on the first oscillator won't be audible in its triangle output, which is the default normalized to the sine shaper, but using firm sync mode would allow the PWM to have an effect, or we can patch the PULS output into one of the sine shaper's inputs as shown. The MIDI gate drives two ADSR envelopes, one for the filter and one for the VCA. The Doepfer VCA used here has two audio inputs so we patch in the low-pass and band-pass outputs of the filter to provide some mixing options.

The sine shaper can process an external input if it's raised to an appropriate level. Depending on how hard it's driven, it can range from just a mild enhancement of odd harmonics, through tube-like foldback, into complete wavefolding. In this example, the three outputs from the shaper go through a Transistor Mixer to mix them down and provide some additional distortion options of its own. Turning down the levels on the Transistor Mixer allows it to knock the level back down to a typical audio "line level" for further connection to non-Eurorack equipment.



Here's a West Coast-style voice emphasizing the modulation effect of the Middle Path sine shaper, with a Leapfrog VCF serving as a low-pass gate. With the pitch CV patched into the left oscillator as shown, it will affect both, so the carrier and modulator will track each other. Another possibility would be to patch it in on the right instead; then it will only affect that oscillator while the other one remains at an unchanging frequency set by the front-panel controls or the Eurorack bus CV.

Through-zero phase modulation is achieved when the slope of the modulator waveform exceeds that of the carrier, so that the phase input to the sine shaper runs backwards. Tune one oscillator to a higher frequency than the other, and adjust the lower-frequency oscillator to a higher input level on the sine shaper, to get through-zero with this patch. The envelope can drive just the filter cutoff for a pure low-pass gate effect, or patch it into the Leapfrog's built-in VCA also for a more extreme cutoff of amplitude as well as frequency (which allows tuning the filter higher).



Quadrature outputs on the Middle Path make it a building block for Bode-type frequency shifter patches. In this example, the master (left) oscillator with its PWM knob turned all the way counterclockwise gives two square waves 90° apart in phase on its SQR and PULS outputs. Those drive two of the inputs on the Doepfer dual ring modulator. The master oscillator's contribution to the sine shaper input is turned off. Meanwhile the slave (right) oscillator drives the sine shaper, whose "sin" and "cos" outputs also go into the dual ring modulator. A Dual Octave Switch functioning as adder/subtractor gives two different mixes of the ring modulator outputs corresponding to frequency shift up and down. If only one of those were desired, a plain unity mixer would suffice.

Because of the approximations involved in this frequency-shift patch, such as using square waves instead of sines for one of the analytic signals, the result will not be a pure frequency shifted spectrum; some components will shift in the "wrong" direction, or not be filtered out. It'll still sound interesting, though. To get a purer result, patch the sawtooth output of the slave oscillator into the corresponding shaper input, overriding the normalization to the triangle output. Then with the level adjusted to make them as close to pure sine waves as possible, the "sin" and "cos" outputs will be just quadrature sine waves suitable for a pure frequency shift. That same technique can also be used for making the Middle Path a quadrature sine oscillator in a more complicated frequency shifter with external input, a Hilbert transformer, and so on.

When tuning the Middle Path to match its V/octave reference point to some known value, for instance to match MIDI notes, it's convenient to listen to the beat frequencies in the sine shaper. Here, the Mutable CVpal in "turbocharged monophonic mode" (MIDI channel 2) produces a pitch CV and also a square wave at the corresponding frequency. We patch the pitch CV to the Middle Path V/octave input (affecting both oscillators), the square wave to one of the sine shaper inputs, and then listen to the sine shaper output and play with the shaper levels and oscillator tuning. Bringing up one oscillator at a time against the square wave makes the beat frequency between them strongly audible, at which point it's easy to tune the oscillator to match the MIDI interface within a fraction of a Hz. Other things instead of a CVpal could easily be used as the reference here – such as other oscillators in a multi-oscillator system.

Circuit explanation

The Middle Path VCO is intended to be usable both as a dual general-purpose oscillator for two voices of subtractive synthesis in the style people call "East Coast," and as a single complex oscillator that combines the functions of the two cores to produce a complex inharmonic spectrum in the style called "West Coast." As such, much of the design emphasis is on versatility and making the sections work well together.

Exponential converter

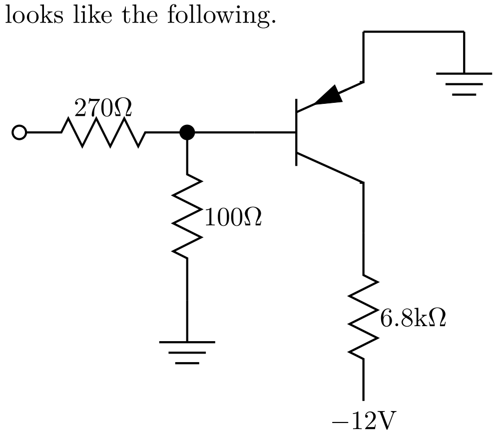
Like most analog oscillator cores, those in the MSK 013 are linearly current-controlled, with an output frequency directly proportional to the input current. The exponential converter section generates control currents for both cores, converting from the exponential voltage control standard of Eurorack. Some circuitry in the converter is shared between the two oscillators in order to help them track each other as closely as possible and to make best use of the expensive THAT320 transistor array chip. Although it should be as frequency-accurate in absolute terms as is normally expected of an analog synthesizer oscillator, the real emphasis in the design is on stability; accuracy in tracking between the two oscillators; and ease of construction and adjustment, especially in a DIY context.

Bipolar junction transistors have a naturally exponential voltage to current function that is surprisingly accurate. The collector current I_{C} of a transistor in relation to the base-emitter voltage V_{BE} basically obeys the equation $I_{\mathrm{C}} = \exp(aV_{\mathrm{BE}} + b)$. But the coefficients a and b vary with temperature and with the individual transistor. To achieve accurate oscillator tuning, we need to compensate for the variation.

The MSK 013 exponential converter uses four transistors that are built into a single silicon chip (the THAT320 transistor array). This chip is specifically meant for this kind of application, and one of its selling points is that the four transistors are made as identical as possible both by design and by testing and selecting manufactured chips. The fact that all four transistors are part of a single silicon crystal keeps them at very nearly the same temperature at all times, because silicon has a very high thermal conductivity. All this means that although the exponential function of the transistors may vary from unit to unit and over time as the temperature changes, it should at least be *the same for all four transistors.*

Then we can use two of the transistors on the chip as references, constantly measuring the exponential curve they are producing, and apply the result of those measurements to compensate the other two transistors (one per oscillator) into producing the desired V/oct function. As the temperature changes, the performance of the transistors will change, but if they stay close to each other and we do the measurement and compensation properly, the overall performance of the exponential converter should not change. The MSK 013's use of *two* reference transistors at two different current levels eliminates the need for precision "tempco" components seen in more common one-reference designs.

In keeping with the desire for all four transistors to exhibit the same voltage/current function, every transistor in the THAT320 runs in an environment that looks like the following.



The input voltage goes through a low-resistance voltage divider that scales it down by a factor of 3.7, in order to allow the circuit driving it to run over a somewhat larger voltage range and be less affected by stuff like op amp offsets. Depending on where the transistor is being used (reference or actually driving

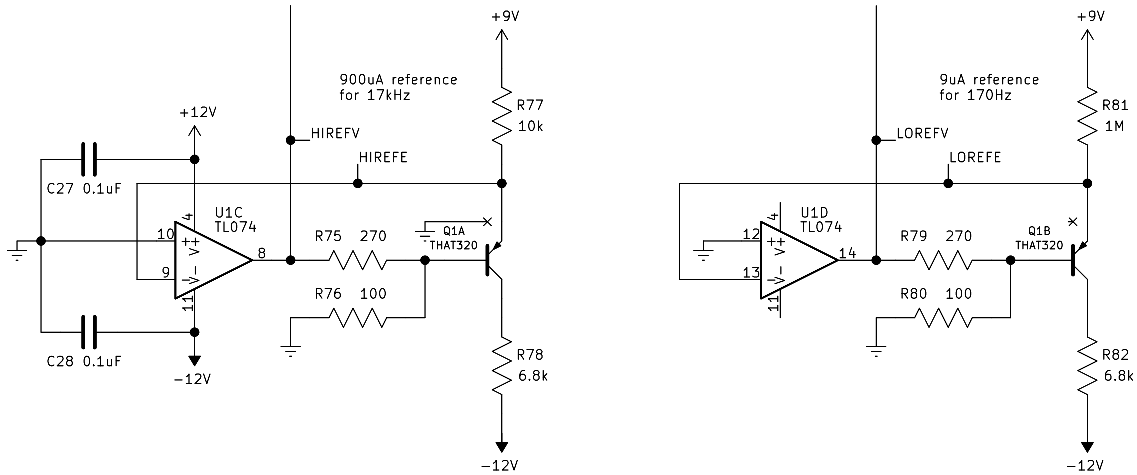


Figure 7: Current references.

an oscillator) the emitter may really go to the ground plane as shown, or it may be kept at 0V by an op amp feedback loop; and the collector may go through the 6.8kΩ resistor to the −12V power supply rail or to the current input of the oscillator core, which is at a similar voltage. The 6.8kΩ resistor is to limit current to a maximum of about 1.75mA, protecting the LM13700 chips which have a maximum rating of 2mA for control current; although such a resistor is not necessary for protection on the reference transistors, they are given such resistors too, to keep them running under conditions as similar as possible to the the conditions of the oscillator-driving transistors.

The reference transistors and their driver circuits are shown in Figure 7. These are straightforward op amp current sources. One end of a current-setting resistor (10kΩ R77 or 1MΩ R81) is driven by a +9V supply, and an op amp controls the exponential transistor to pull the other end to 0V. Thus the circuit is finding a voltage to answer the question "What input voltages does it take to make transistors on the THAT320, at whatever temperature they are at right now, pass 9μA and 900μA?"

From those two voltages, we can interpolate to get the transistor voltage for any desired current level. For example, to get 90μA from an oscillator-driving transistor, we would use a voltage at the midpoint of the voltages for 9μA and 900μA. Even if temperature changes cause the voltages to change, as long as we track that midpoint we can expect the output current to remain 90μA. The voltage for either of the two current references can provide an offset (b coefficient in the transistor's curve), and the difference between them provides the scale factor (a coefficent). The higher current, 900μA, is two decades or 6.644 octaves from the lower current; so the voltage change on a transistor's voltage divider input to give one octave of change in output current, will be 1/6.644 of the difference in reference voltage for the two current levels.

Actually doing the interpolation requires some analog computation, which in this design is performed by an AD633 analog multipler chip. The AD633 is a very expensive precision component, but it's a nearly foolproof drop-in module that does the whole task on one chip, significantly reducing the complexity of the circuit compared to other ways of getting a similar effect. A lot of the money spent on the multiplier chip is saved in labour adjusting and debugging a more complicated exponential converter.

The AD633's basic function is that of multiplying two factors to get one product, but both factors and the product are differential voltages, so it actually has six pins devoted to the calculation (five inputs and one output) and within its normal range of operation its behaviour is described by the equation $W = Z + (X1 - X2) \cdot (Y1 - Y2)/10V$. The difference in volts between the X1 and X2 inputs, times the difference between Y1 and Y2, divided by 10 volts, plus the voltage at Z, appears on the output W. See Figure 8 for one of the two channels of the exponential converter using this chip.

The two voltages from the current references are applied to the Y1 and Y2 inputs, so the analog multiplier is scaling its X input in proportion to the difference in voltage that it takes to increase current

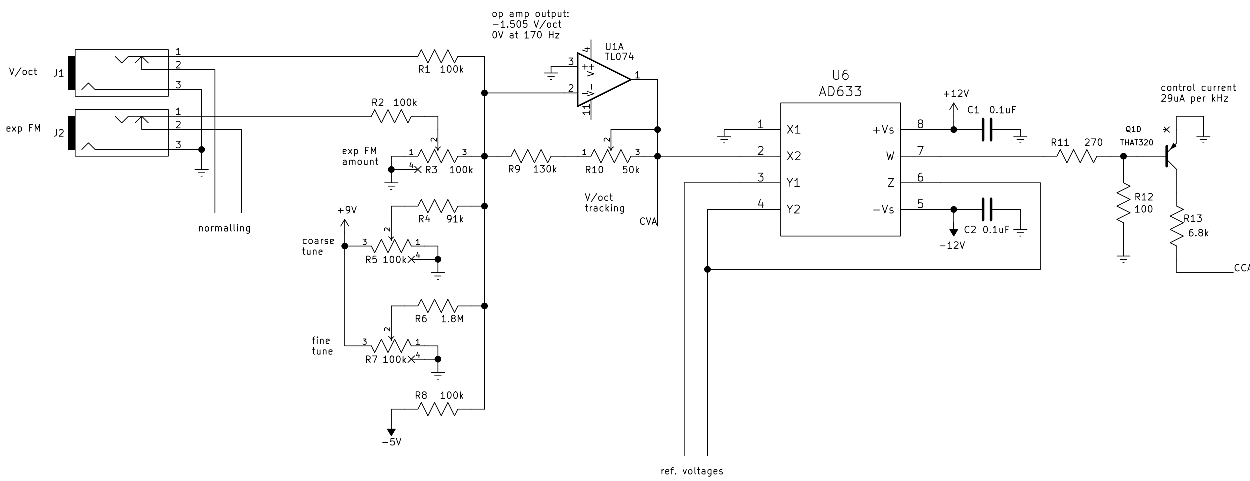


Figure 8: Exponential converter.

by a factor of 100. That X input comes from a straightforward DC mixer which combines the settings of coarse and fine tuning knobs, the V/octave and attenuated exponential FM control voltages, and a fixed offset (derived from a −5V reference) to set the overall range of the tuning controls. The voltage is applied to the X2 pin with the X1 pin at ground, in order to get the right sign on the eventual output voltage.

The output of the DC mixer is scaled to nominally −1.505V/octave; with the division by 10V built into the AD633, this means each octave of control voltage change corresponds to 0.1505 fraction of the 6.644 octaves between the two reference currents, which does work out to one octave. The exact tracking can be adjusted with the trimmer in the op amp loop.

On the output side, the voltage for the 9μA current reference is also applied to the Z input of the AD633, so when the result of the multiplication is zero (because the op amp output was at zero), the AD633's W output just tracks Z and the control current is 9μA. That sets the offset for the control circuit: 0V from the op amp corresponds to 170Hz, and this offset automatically adjusts to follow any changes in the voltage for 9μA that might come from temperature changes.

Some sources of error are still possible in this design, including from inaccuracies in the AD633, temperature effects on components other than the THAT320, and so on. It is not the absolute most accurate exponential converter possible. But in practice, it works well, especially in the musical frequnecy range of about 100Hz to 1kHz, and it requires very little adjustment or guesswork.

Triangle cores

The MSK 013 uses triangle-wave analog oscillator cores both as a musical choice and to improve accuracy. The triangle waves are close to sinusoidal, low-harmonic waveforms suitable for shaping and modulation to add harmonics in the sine shaper. They also tend to track better than basic sawtooth cores because instead of having a reset period, they have two reversals per cycle; those reversals happen faster than a reset and are easier to control, giving usually better accuracy from a triangle core at a given level of circuit complexity.

The slave triangle core is shown in Figure 9. The master is identical, minus the sync circuit.

Like most triangle cores, this one is a loop of three stages: an integrator that keeps track of the instantaneous voltage of the triangle waveform; something (in this case a Schmitt trigger) to remember which direction the waveform is moving and decide when to change directions; and a variable amplifier that calculates the speed and direction the triangle voltage should change based on pitch control input.

The LF353 op amp U9A serves as the inverting integrator. It accumulates a voltage in the 1200pF capacitor C19 that rises when the input to the integrator is negative and falls when the input is positive, at a rate proportional to the magnitude of the input voltage. The output from this op amp is tapped off to drive U3A, a buffer amplifier, which distributes it to the external triangle-output jack and to the internal TRIB signal, used for normalling the sine shaper.

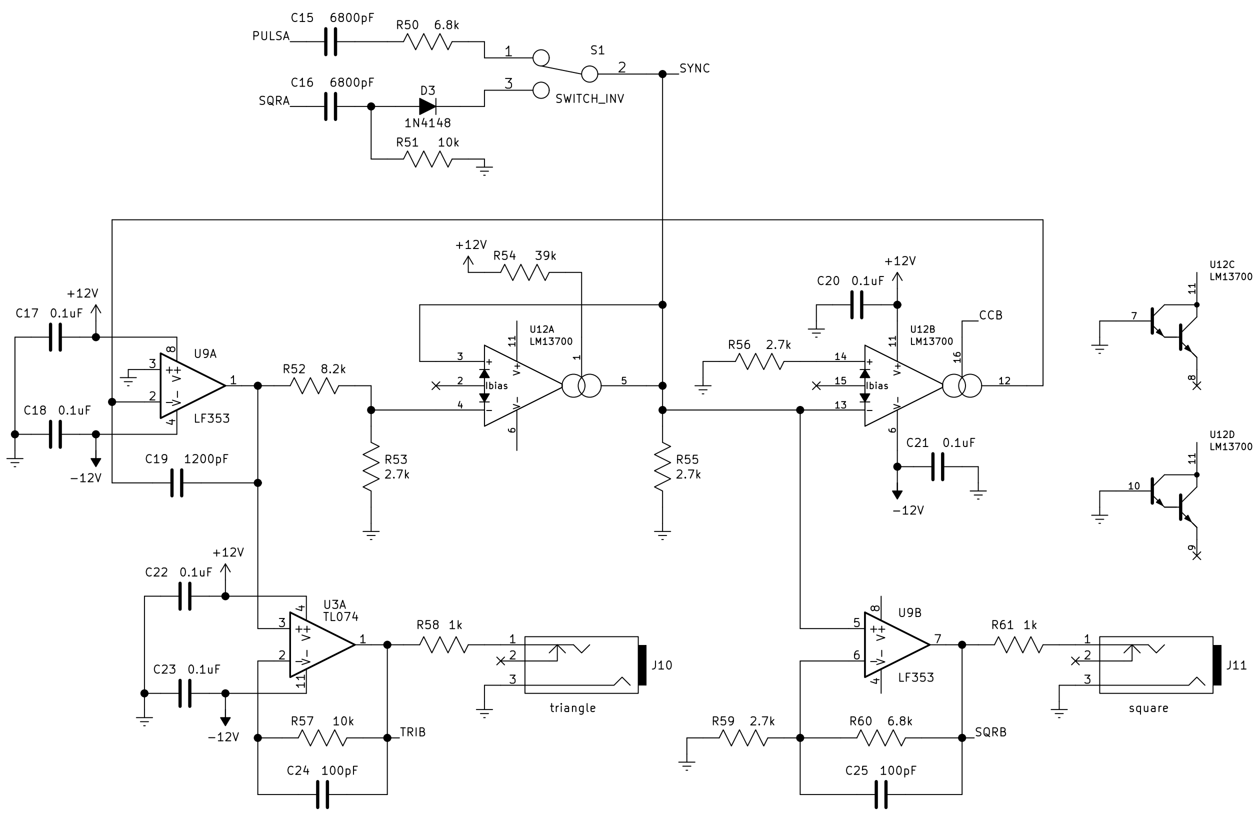


Figure 9: Triangle oscillator core.

Note that this op amp has an RC network of R57 and C24 in its feedback loop instead of just using a plain wire from output to negative input; that is for stability in case of weird reactive loads being connected to the external jack socket.

The output of the integrator also goes through a voltage divider made up of R52 and R53 to bring it to the right level for input to U12A, an LM13700 operational transconductance amplifier (OTA) configured with positive feedback to function as an inverting Schmitt trigger. In a single stage this amplifier both detects the upper and lower bounds of the triangle waveform, and remembers the current state.

An OTA like the LM13700 works by routing the control current, in this case coming from R54 and the positive supply, through current mirrors to shift its direction and voltage. For small differential input voltages it produces a more or less linear amplifying effect, but the voltage differences on the inputs are relatively large in this circuit, and the OTA is basically a switch. With the positive input at higher voltage, the OTA sources an amount of current equal to the control current. With the negative input higher, it sinks the same amount. It has a high impedance either way, meaning that the current through the output does not depend much on the output voltage.

Suppose the output of U12A is at positive voltage, and in particular, higher than the scaled integrator voltage. Then U12A's positive input is at higher voltage, U12A sources current into R55, and that produces a positive voltage. The feedback loop forces U12A's output to go as high as it can go. A rough calculation would put the control current at 24V divided by 39kΩ, which is 615μA, and then the output voltage is 2.7kΩ times that, giving +1.66V. Similarly, when the output is low, the feedback loop forces it to go as low as it can, to −1.66V. In practice, that calculation gives only an approximate value, among other reasons because the LM13700's control input is not really quite at the negative power rail. The Schmitt trigger output really only swings to about ±1.5V.

That output voltage is being compared against the scaled integrator output, as seen through the voltage divider of R52 and R53. When the integrator goes above about +6V (the nominal 1.5V Schmitt trigger threshold times the 4.03 division factor of R52 and R53), the Schmitt trigger switches to negative output, and when the integrator goes below −6V, the Schmitt trigger switches to positive output. There is some slippage in the voltage here too, and the voltage swing as seen at the buffered triangle output is really more like ±5.5V. One reason is that as the integrator voltage gets close to the threshold, the LM13700 stops functioning purely as a switch, its output current decreases, and that reduces its output voltage, bringing the threshold closer to the integrator voltage and making it switch earlier.

The Schmitt trigger output also drives U9B, a non-inverting amplifier which boosts it to about ±5.5V for the "square wave" external output, and U12B, which is a simple current-controlled amplifier that takes the control current from the exponential converter and switches its direction depending on the state of the Schmitt trigger, to apply to the integrator input.

The overall cycle of the oscillator runs as follows. At some point the Schmitt trigger output is positive. U12B sinks current, in an amount determined by the exponential converter. That causes the voltage output of U9B to rise. When it reaches about +5.5V, the Schmitt trigger switches to negative output. Then U12B sources current instead of sinking it, causing the voltage output of U9B to fall. When it reaches −5.5V, the Schmitt trigger switches to positive again and the cycle can repeat. So the integrator output is a triangle wave, bouncing between ±5.5 with a slope determined by the current from the exponential converter, and the Schmitt trigger output is a square wave, positive when the triangle is rising and negative when it is falling. The speed of the entire cycle is proportional to the current from the exponential converter, and that proportionality is quite exact over at least the entire audio frequency range, 20Hz to 20kHz.

Sync

The switch S1, shown near the top of Figure 9, selects either of two simple sync circuits, or no sync in the centre "off" position.

In *firm* sync mode, S1 selects C15 and R50, which form a simple high-pass filter. The internal PULSA signal, representing the pulse shaper output of the master oscillator, gets coupled through these components to the Schmitt trigger of the slave oscillator. When the master pulse output goes high, a current spike is applied across R55, forcing the Schmitt trigger into the high state and the slave oscillator into the rising state of its cycle. Similarly, when the master pulse output goes low, a current spike in the other direction passes through C15 and R50, forcing the slave oscillator Schmitt trigger into the low state. I call this firm sync because it has a relatively strong effect on the slave oscillator's phase, making it lock quickly to the master, but it does not reset the integrator to a fixed voltage immediately like the true hard sync typical of saw-core oscillators. The exact spectral effect of firm sync will vary depending on the pulse width (and pulse width modulation) of the master oscillator.

In *soft* sync mode, the master square wave (not pulse) output goes through C16, R51, and D3. The diode allows pulses to pass only on the rising edge of the square wave. The resistor allows the capacitor to recharge on the opposite pulse edge. Here the slave is only switched to the rising state once per cycle of the master, so it takes longer to lock.

In either mode, because the sync pulses are applied directly to the Schmitt trigger output of the slave oscillator core and that is also the source for the slave oscillator's square wave output, the sync pulses will appear in the square wave, often pushing its voltage outside the usual range of approximately ±5.5V. Sync pulses can also hold the slave oscillator in a given state briefly even when the integrator voltage would normally switch its direction; as a result, the slave triangle output can also go out of its normal voltage range when in sync mode.

Pulse and sawtooth shapers

Each oscillator core has a sawtooth shaper, which converts the triangle and square wave outputs from the core into a sawtooth waveform. The sawtooth shaper from the master oscillator is shown in Figure 10; the slave's is just the same.

The op amp U2B is set up as an inverting amplifier with a gain (determined by the ratio of R27 and R24) of −0.5. There is also a negative offset created by current from the +9V reference through R25 and R26; so the triangle wave which comes in at nominally ±5.5V is shifted and scaled to cover the range −5.5V to 0V.

The op amp U2C is either a unity-gain amplifier or an inverter, depending on the state of Q2. This MOSFET functions as a switch: with the square wave high, the MOSFET conducts, holding the positive input of U2C at 0V. In this state, U2C functions as an inverter with gain −1, as set by R29 and R30. When the square wave goes low, Q2 turns off. Then the positive input of U2C stays at the output voltage of U2B; and in order to keep the negative input at that same voltage, U2C must also track the output voltage of U2B; the amplifier has gain +1.

Now, consider the progress of an oscillator cycle, starting at the high peak of the triangle wave. In the falling phase, the triangle goes from +5.5V down to −5.5V and the square wave is low. The output of U2B (inverted, scaled, and shifted) goes from −5.5V up to 0V. The MOSFET is turned off, so U2C acts as a unity-gain buffer for the U2B voltage, and the sawtooth output rises from −5.5V to 0V. Then the triangle reverses direction, rising from −5.5V up to +5.5V. The output of U2B goes from 0V down to −5.5V. The square wave is high now, turning on Q2, and U2C functions as an inverter; the sawtooth output continues rising from 0V up to +5.5V.

The waveforms in Figure 10 illustrate the operation of the shaper. There is usually a small glitch when the sawtooth crosses zero because of timing inaccuracy between the triangle and square signals, and the nonzero time required to switch between the inverting and noninverting configuations of U2C. The offset trimmer R25 can be adjusted to minimize this glitch and line up the two halves of the sawtooth as accurately as possible.

The pulse shaper for the master oscillator is shown in Figure 11; that for the slave is just the same. This circuit is basically just an op amp working as a comparator, with its support components. Many sources advise against using op amps to compare voltages instead of special-purpose comparator ICs, among other reasons because an op amp driven to its maximum or minimum voltage can "saturate" and then take longer to come out of that state than its usual response time. But after testing several alternatives, it really seems the straightforward op amp as comparator is the best design for this circuit in this particular application. With the specified TL074 chip, the response time coming out of saturation is more than fast enough for even the highest audio frequencies.

The reference voltage from J5, either an input PWM signal or the normalization voltage, is attenuated by R33 and R34 and applied to the negative input of the op amp. So is the oscillator triangle output, through R35. If the average of these two voltages is above zero, the op amp output goes strongly positive; if below, it goes negative. Then D1 and D2 serve to clip the voltage to approximately ±5.6V. The resistor R141 limits the current from the op amp output, and R26 limits the current through the output jack (especially in the case where somebody patches it into a power supply).

Quadrature sine shaper

The Middle Path VCO's quadrature sine shaper is

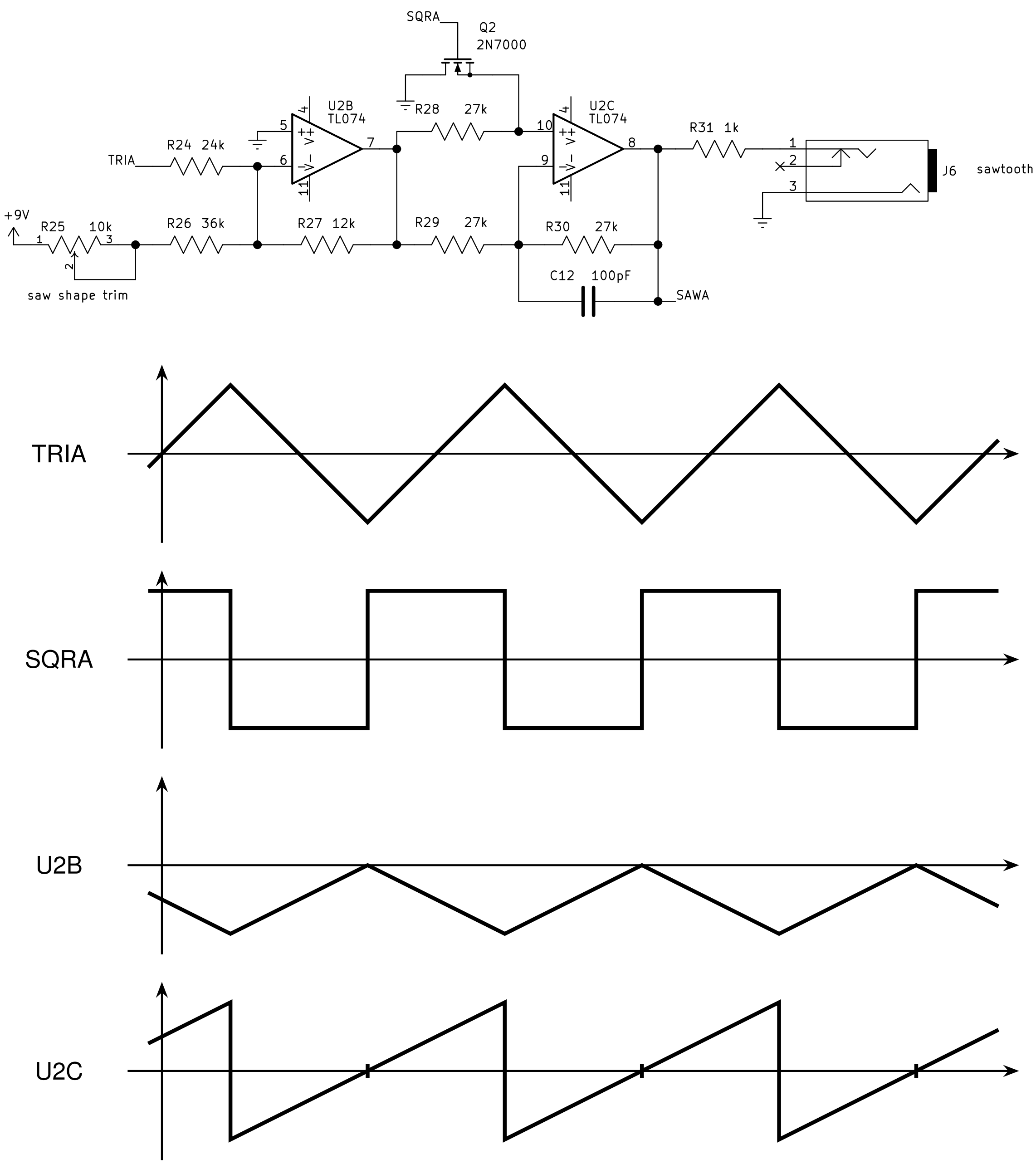


Figure 10: Sawtooth shaper with its waveforms.

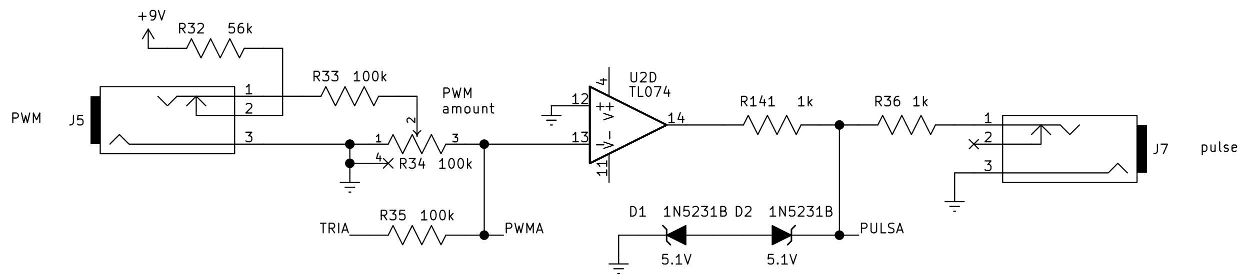
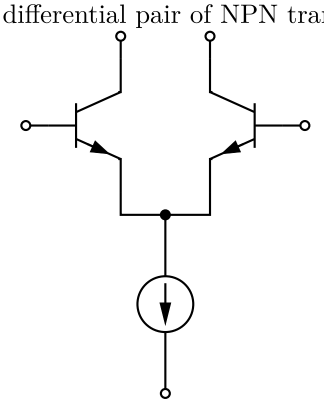


Figure 11: Pulse shaper.

probably the most innovative part of the module, and key to its unique sound and feature set. There is a lot going on in this circuit, but it can be thought of as a straightforward evolution from a simple, familiar analog building block: the differential pair.

Here's a differential pair of NPN transistors.



The current sink at the bottom draws a fixed amount of current through the two transistors combined. Excluding whatever flows through the bases (which should be negligible if the transistors have reasonably high gain), the sum of the two collector currents of the transistors will be forced equal to the constant current of the current sink. The emitters of the transistors, which are joined, will naturally float to whatever voltage it takes to make that work.

But the split between the two transistors, how much of the total current goes to which transistor, will be determined by the difference in voltages applied to their bases. If the base voltages are equal, the current should split 50/50. If one base is about 18mV more positive (assuming silicon transistors at room temperature), then the current through that transistor will be twice as much as the current through the other transistor; that is, two thirds of the total. Note that each transistor's share is an exponential function of its base voltage relative to the other transistor.

The split depends on the *difference* in base voltages but not on the *absolute value* of the base voltages; if both bases go up or down by the same amount within the limits of the circuit, the proportional split between the two transistors does not change. The proportional split also should not change if the current sink's current changes; both transistor collector currents scale in proportion to the total. Depending on the application, it's expected that some stage further downstream will capture the currents flowing through either or both collectors and do something useful with the result.

The basic differential pair is commonly seen at the input of an op amp circuit. It can also be used to build a VCA or multiplying circuit: one factor to be multiplied gets applied as a base voltage and the other is used to control the current sink, possibly through a current mirror.

What if we generalize the circuit to use more than two transistors? All emitters will be connected together with a constant current sink drawing a fixed current through the collection of transistors. The current into the current sink splits more than two ways, some flowing through each transistor. The basic principle remains the same as in the two-transistor differential pair: the sum of all the collector currents, excluding negligible currents through the bases, must be equal to the current-sink current, and the joined emitters of all the transistors will float to whatever voltage it takes to make that equation true. And then the difference in base voltages will determine the proportional split among the transistors; whichever transistor has the highest base voltage gets the most current, and others get less, in proportion to an exponential function of how much their own base voltages are below the highest.

If we could give just one transistor a significantly higher base voltage than the others, that transistor would get almost all the current-sink current. If we gave relatively high base voltages to *two* transistors, they would split the current, in proportions determined by any difference between their base voltages. In general, the one or more transistors with the highest base voltages will split the current and any others with significantly lower base voltages will be turned off, passing effectively no current. Barrie Gilbert patented a well-known sine waveshaping circuit based on this principle (US Patent #4,475,169A, now long since expired): a differential "pair" generalized to use more than two transistors, with the current split among the transistors used to smoothly interpolate between the peaks of the desired voltage function.

Consider the resistor network shown in Figure 12. It is assumed that driver amplifiers not shown apply an input voltage to one end of the network, and the opposite of the input voltage to the other end. Current flows from one end to the other, through a chain of resistors of relatively low value, so that effect alone should cause the voltages along the chain to interpolate linearly from the input voltage to its negative. But there are also resistors of relatively high value pulling up the voltages along the chain toward +12V. Near the ends, the low impedance from the driver circuits prevents those pull-ups from having much effect. But toward the centre, there is less influence from the drivers and the pull-ups are more able to raise the voltage.

The overall behaviour of this network (illustrated for three different input voltages in the figure) is that the voltages at different points along the chain will approximate a parabola or quadratic function, with a peak that shifts left and right, toward one end of the chain or the other, according to the input voltage.

In the Gilbert sine shaper, the voltages from this kind of network are applied to the bases of transistors in a many-transistor generalized differential pair. At zero input, the peak in voltages is in the middle of the chain; as the input goes positive or negative, the peak moves forward and backward along the chain. Transistors at or near the peak split up the current; transistors further away from the peak are turned off.

The next step is that in Gilbert's version of the circuit, the current outputs from alternate transistors are *summed* by connecting them together. All the even-numbered transistors drive one current output, and all the odd-numbered transistors drive the other. And then another differential amplifier computes the difference between the even-transistor and odd-transistor currents.

Think about what happens as the input voltage increases. The peak in base voltages moves along the chain. When it hits an even-numbered transistor, that transistor carries most of the current-sink current, and so the even-transistor group is carrying more current than the odd-transistor group and the difference is maximized in one direction (let's say positive). As the peak continues moving, it will hit an odd-numbered transistor. Then that transistor carries most of the current, so the odd-transistor group carries most of the current, and the difference is now maximized in the other direction (let's say negative). The output of the Gilbert shaper switches back and forth several times as the input voltage moves across its range.

The peak of the base voltages doesn't really activate just one transistor at a time; other transistors on either side of the peak will always also be conducting to some extent. That reduces the overall output voltage because the difference between the even and odd groups will never be overwhelming; but it also means that the interpolation between positive and negative peaks is smooth. The cool thing is that the math works out such that within reasonable limits, the interpolation is not only smooth but *sinusoidal.* Within the limits of the circuit, for a number of cycles that is determined by the number of transistors used, and subject to scaling, the Gilbert sine shaper computes something very close to $V_{\text{out}} = \sin V_{\text{in}}$.

The *quadrature* sine shaper used in the Middle Path VCO takes the sine shaping circuit another step further, by grouping the transistors into four groups instead of two. As far as I know, this idea is original with me, although it's sufficiently obvious that I wouldn't be too surprised to hear someone else had thought of it earlier. The core of the quadrature sine shaper circuit is shown in Figure 13.

In the quadrature shaper, there are twelve transistors in the chain, assigned to four groups in a rotating pattern. All the collectors for Group 1, being the first, fifth, and ninth transistors along the chain, are connected together, so the collector currents for those transistors add up, appear as a voltage across R116, and then a unity-gain op amp buffers the resulting voltage to produce an internal signal called GROUP1. The remaining transistors are similarly gathered into groups of three to generate summed and buffered voltage signals.

Note that GROUP1 and GROUP3 *together* cover all the odd-index transistors (counting the first transistor on the left as index 1), and GROUP2 and GROUP4 together cover all the even-index transistors. So if we compute the sum of the GROUP1

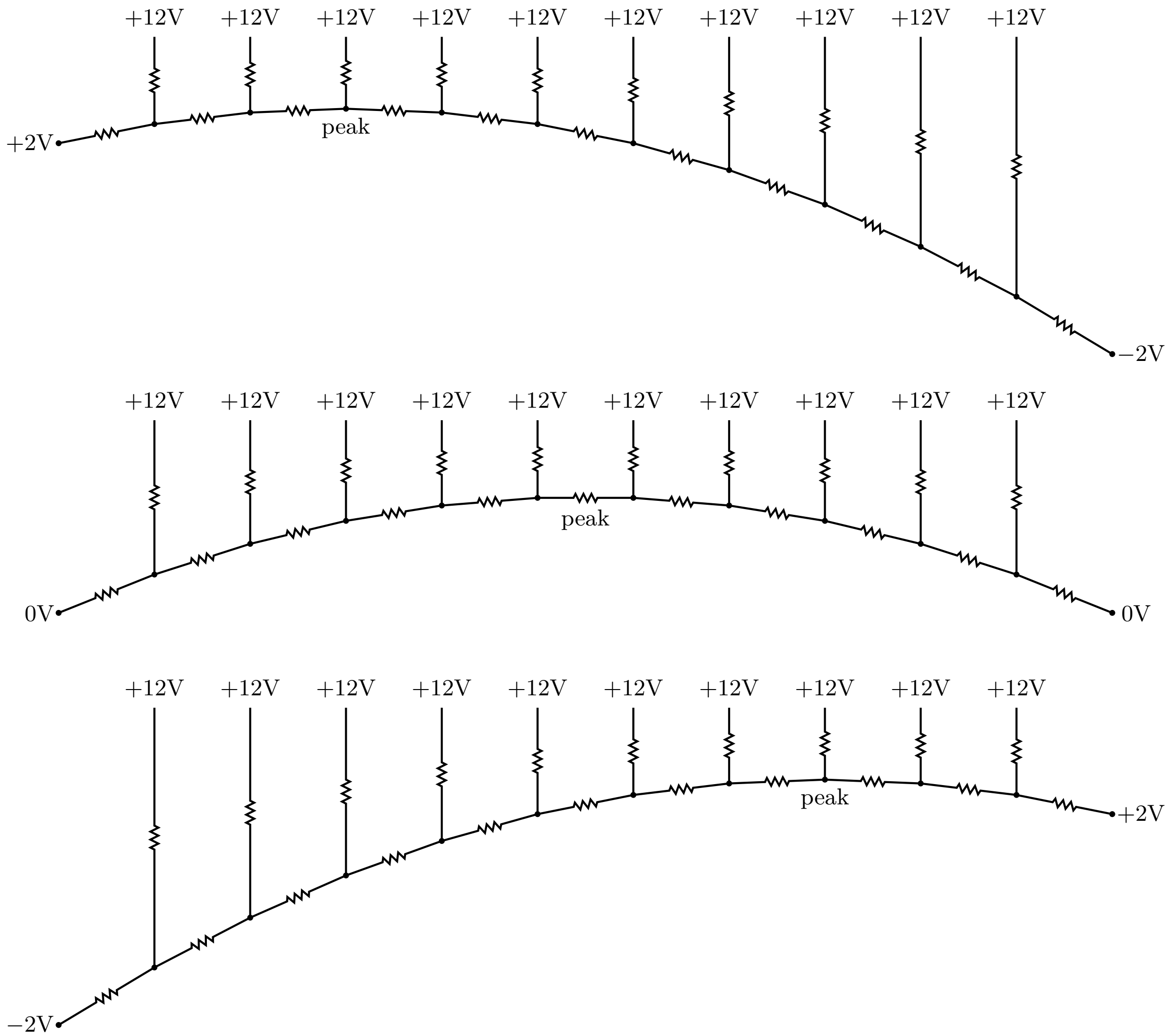
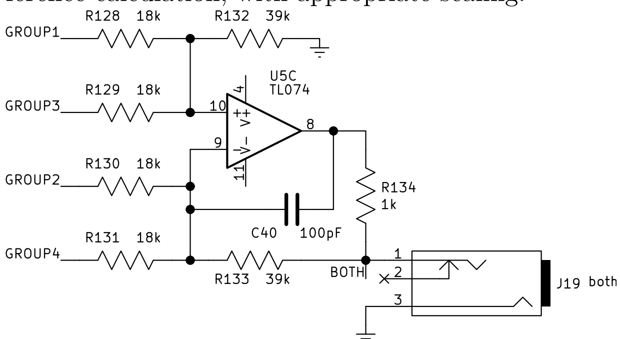


Figure 12: Transistor base voltages in the sine shaper.

and GROUP3 voltages, minus the GROUP2 and GROUP4 voltages, we end up with just the odd transistors minus the even transistors and that is the same result we could get from the basic one-output Gilbert sine shaper. The op amp U5C does that sum and difference calculation, with appropriate scaling.



But GROUP1 and GROUP3 can also be considered separately. The odd-index transistors are all assigned to one of those two groups, but they alternate between them: the transistor at index 1 is in GROUP1, then the one at index 3 is in GROUP3, then the one at index 5 is in GROUP1, and so on. GROUP1 and GROUP3 can be said to be the odd and even transistors within the larger “odd” group. Similarly, GROUP2 and GROUP4 are the odd and even transistors within the larger “even” group.

So we can get two more sine-function outputs by taking the difference between GROUP1 and GROUP3, and the difference between GROUP2 and GROUP4. The op amp U5D does this calculation for GROUP1 and GROUP3; I don’t show U5B here but it works the same way on GROUP2 and GROUP4. These are the module “sin” and “cos” outputs. They each have three cycles along the length of the transistor chain, because there are three transistors in each group; but because the cyclic assignment of transistors to groups is shifted by one quarter cycle (one transistor position) between the two outputs, their sine functions are 90° out of phase. The frequency of these sine functions, relative to input voltage, is half that seen on the “both” output because the “both” output is using six transistors per group.

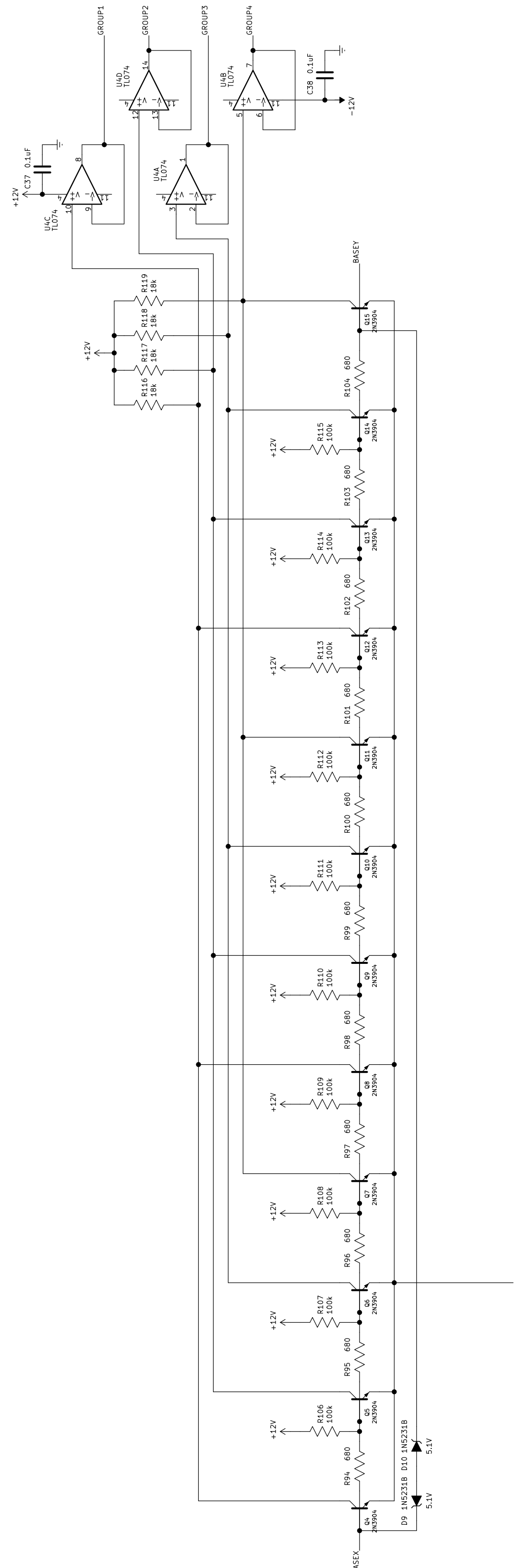
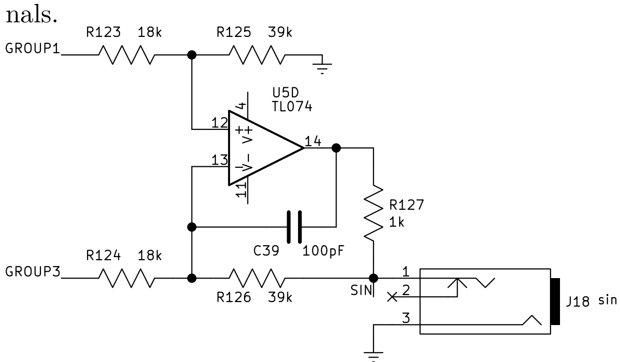


Figure 13: Quadrature sine shaper core.

Here is the mixer for the "sin" output; the mixer for "cos" is similar, but uses the other two group signals.



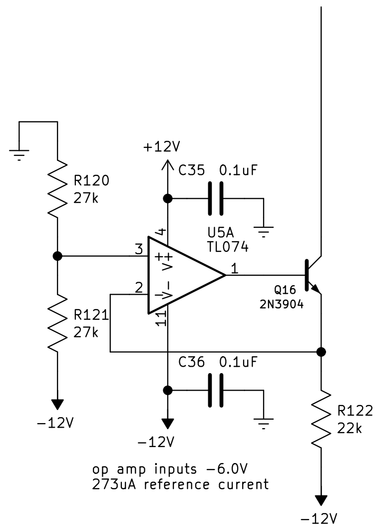
The cyclic assignment of transistors to four groups is the key concept in the quadrature sine shaper. There are just a few other things to mention in the shaper circuit and they are fairly straightforward. Note the clipping diodes D9 and D10, from the transistor at one end of the chain to the other. Those are to prevent reverse breakdown in the transistors. Remember that the voltage on the joined emitter of all the transistors will always be basically one diode drop lower than the peak base voltage along the chain. At an extreme high or low input voltage, the peak is driven all the way to one end of the chain, and will be basically equal to the absolute value of the input voltage. The other end of the chain gets the negative of that; so the transistor there will be seeing twice the input voltage, minus one diode drop, in reverse across its base-emitter junction.

The 2N3904 transistors used here are only rated for 6.0V in that direction; more voltage and they can be damaged. Many other common transistors have an even lower breakdown voltage, which is why I specified 2N3904 in particular for these. Higher-gain transistors which might usually be considered higher "quality" are likely to have low breakdown voltages because gain and breakdown voltage are both determined largely by the level of emitter doping. Increasing one tends to decrease the other.

The diodes D9 and D10 protect the transistors because on out-of-range input voltages they will conduct and clip the voltage difference seen by the ends of the transistor chain to about 5.7V; the maximum reverse voltage on the transistor junctions is then about 5.1V and safely within the transistor specifications.

The input voltage range needed to cover the whole transistor chain is basically proportional to the number of transistors and the size of a diode drop. In the original Gilbert design it's not the usual practice to have so many transistors as I am using here, so the input voltage can be scaled down more and still cover the whole chain. In the quadrature design, there are basically twice as many transistors needed for the same number of sine cycles, and that means scaling the input voltages larger and coming closer to the reverse-breakdown limits of the transistors.

The current sink is a straightforward design in which an op amp drives a transistor base to keep the voltage across a resistor constant.



Finally, the shaper input mixer (Figure 14) is a conventional inverting op amp design with a second inverting op amp to compute the voltage for the other end. Note both ends have 680Ω resistors to limit the current when the clipping diodes turn on.

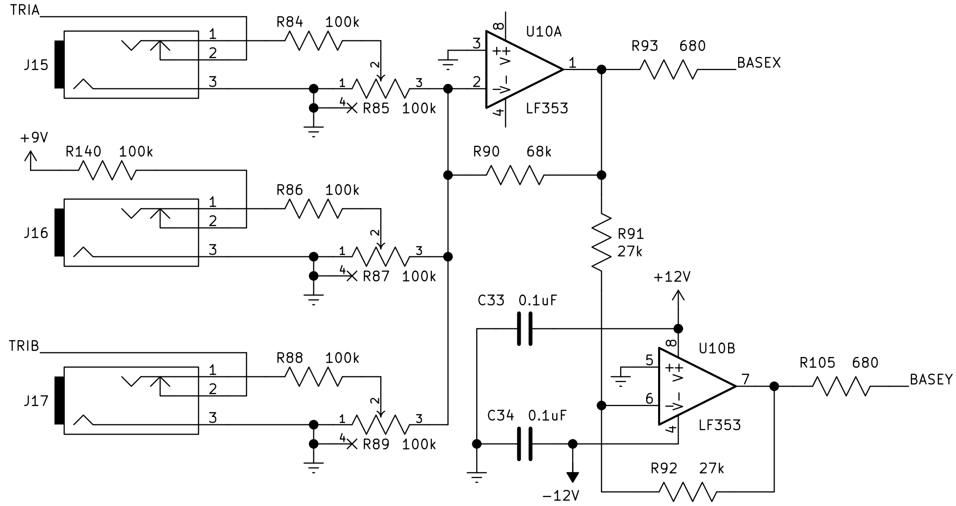
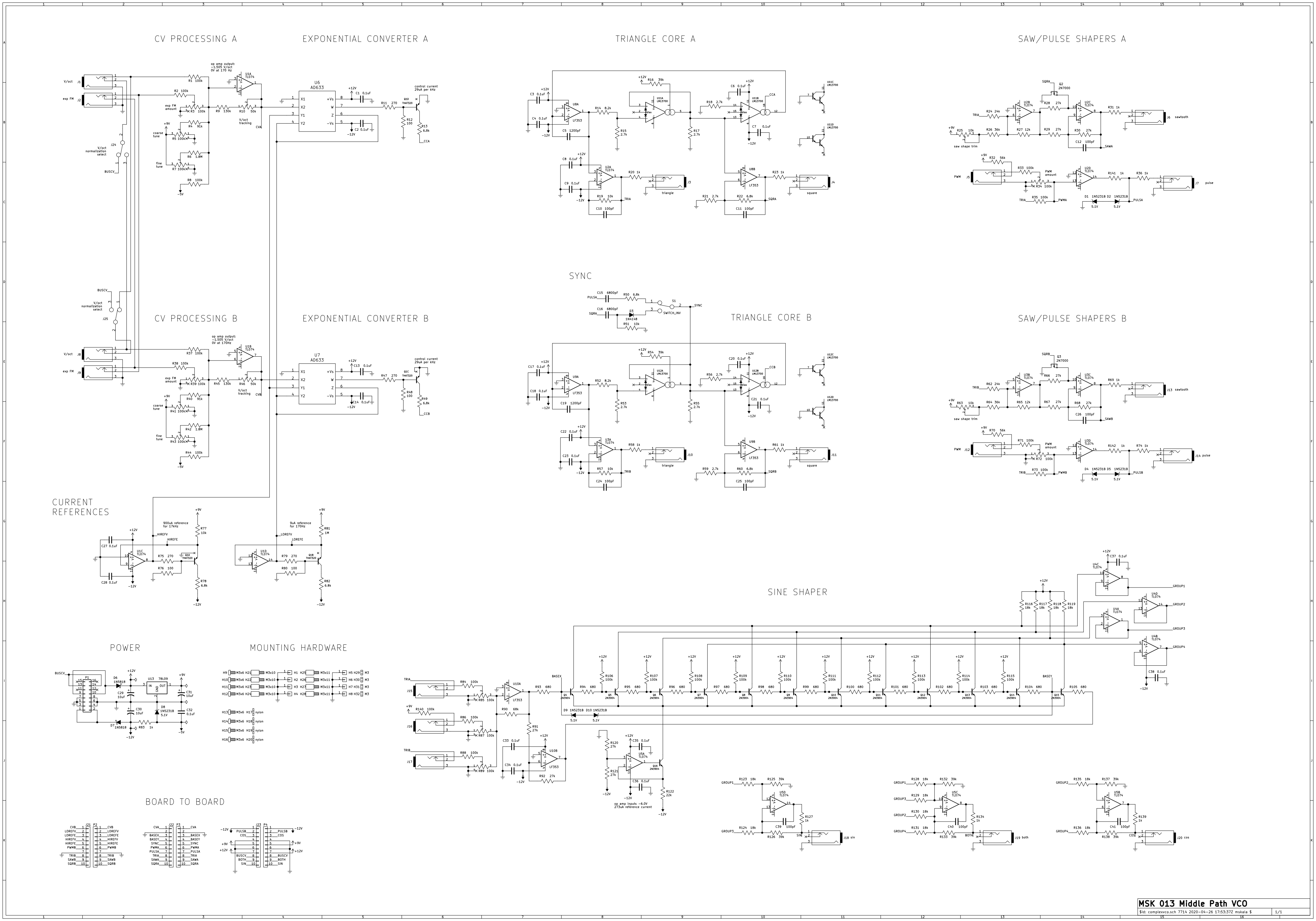


Figure 14: Quadrature sine shaper input mixer.

Mechanical drawings

On the following pages you will find:

- the schematic diagram for the module;
- a mock-up of what the completed module looks like from the front panel;
- the top-side silk screen art showing component placement;
- the bottom-side silk screen art showing component placement (*note this drawing is mirrored, and shows what you actually see looking at the board, not the X-ray view used in other Kicad output*);
- a drawing of the front panel, with the hole locations and other information for manufacturing it; and
- an exploded isometric drawing showing how the boards and hardware fit together.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EXPONENTIAL CONVERTER A
TRIANGLE CORE A
SAW/PULSE SHAPERS A
SYNC
CV PROCESSING B
EXPONENTIAL CONVERTER B
TRIANGLE CORE B
SAW/PULSE SHAPERS B
CURRENT REFERENCES
SINE SHAPER
POWER
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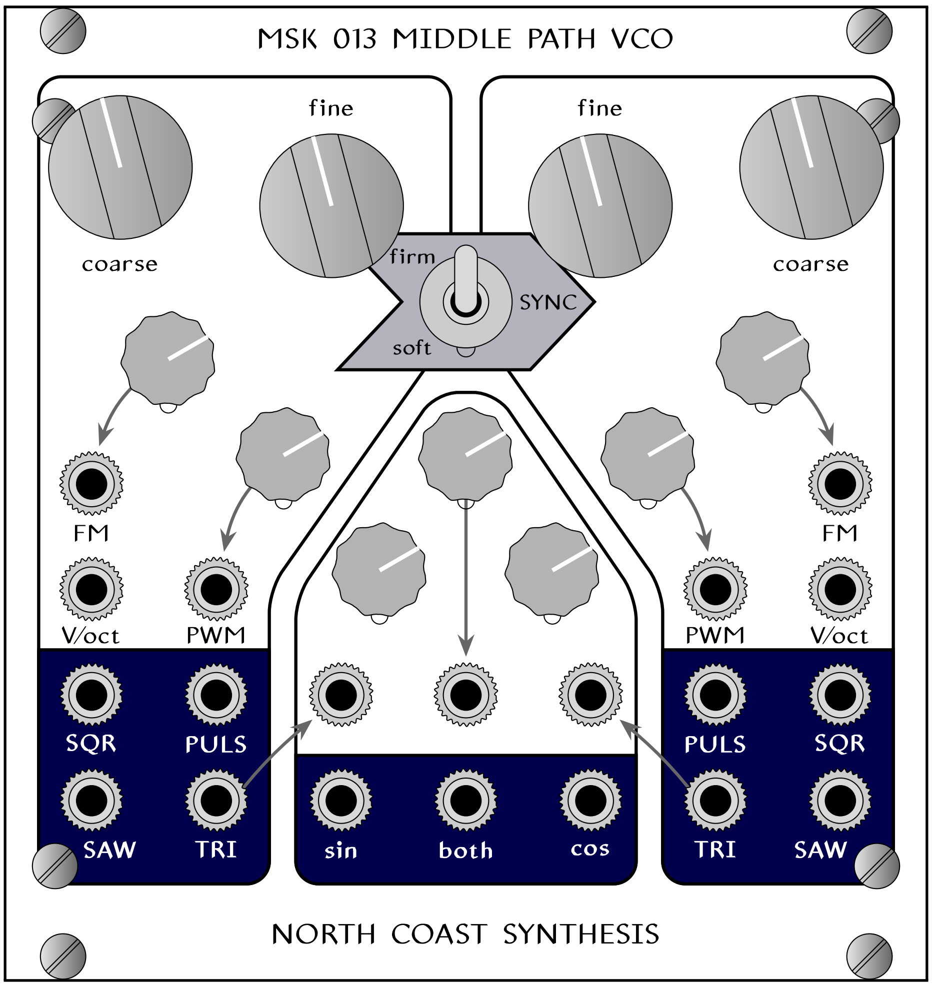
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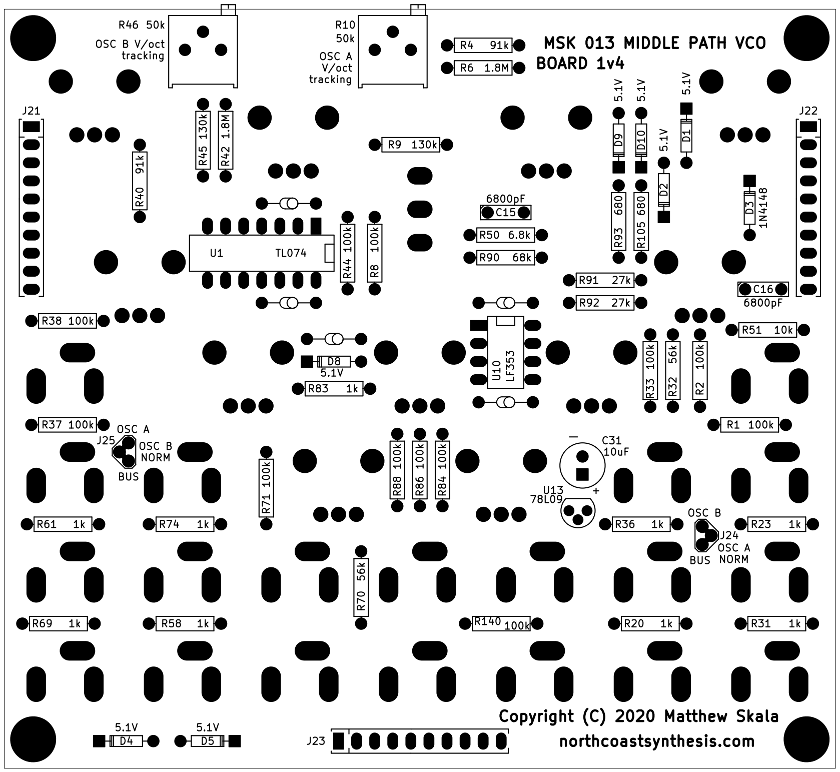

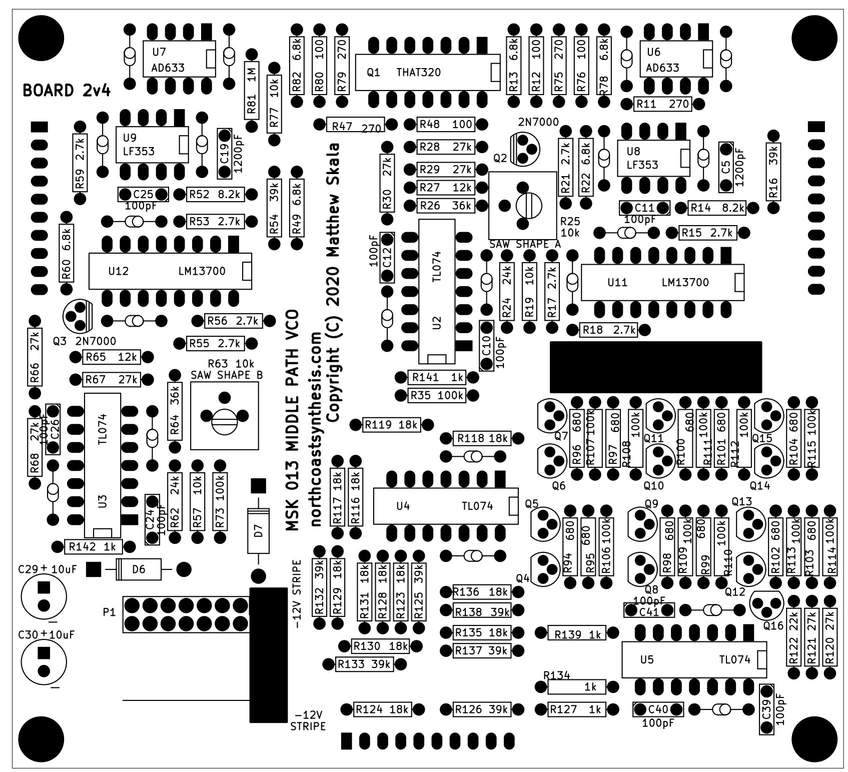

MSK 013 Middle Path VCO

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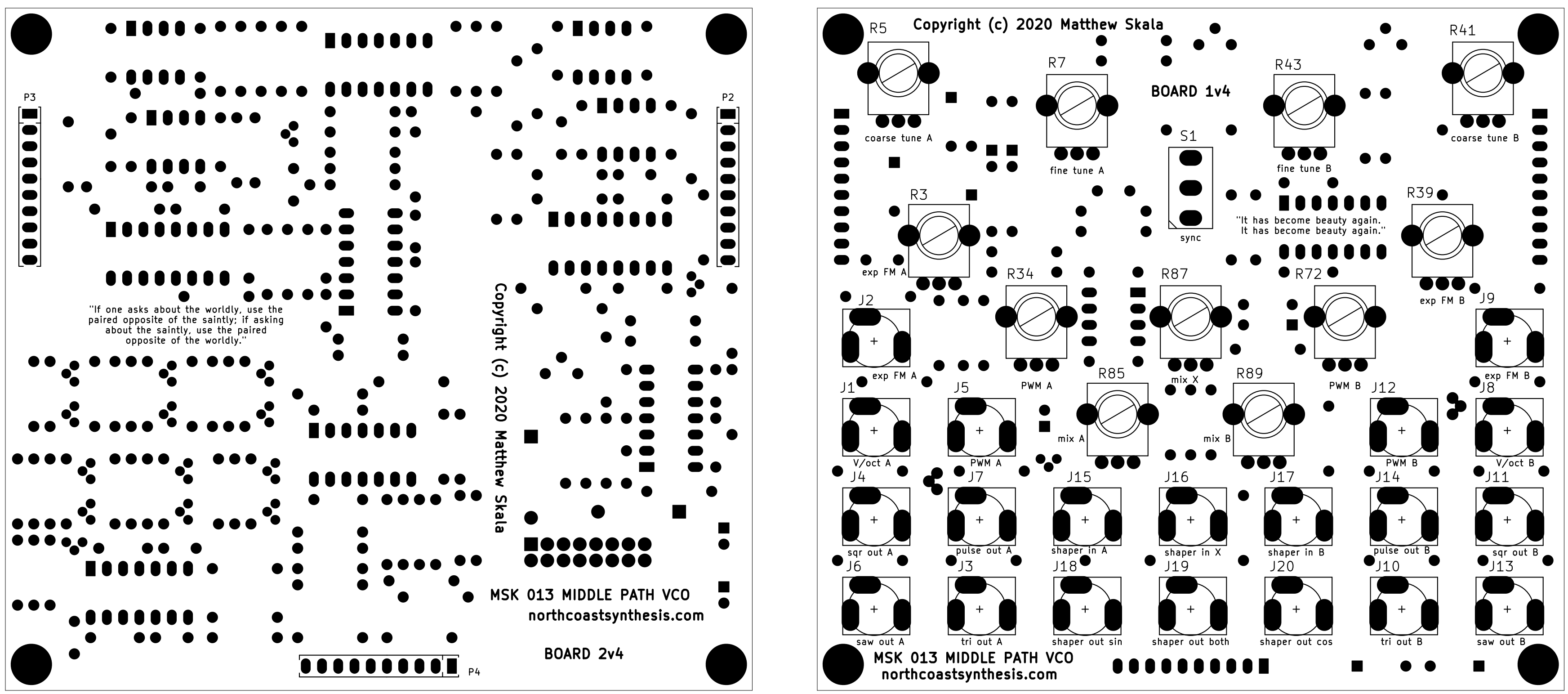

MSK 013 Middle Path VCO

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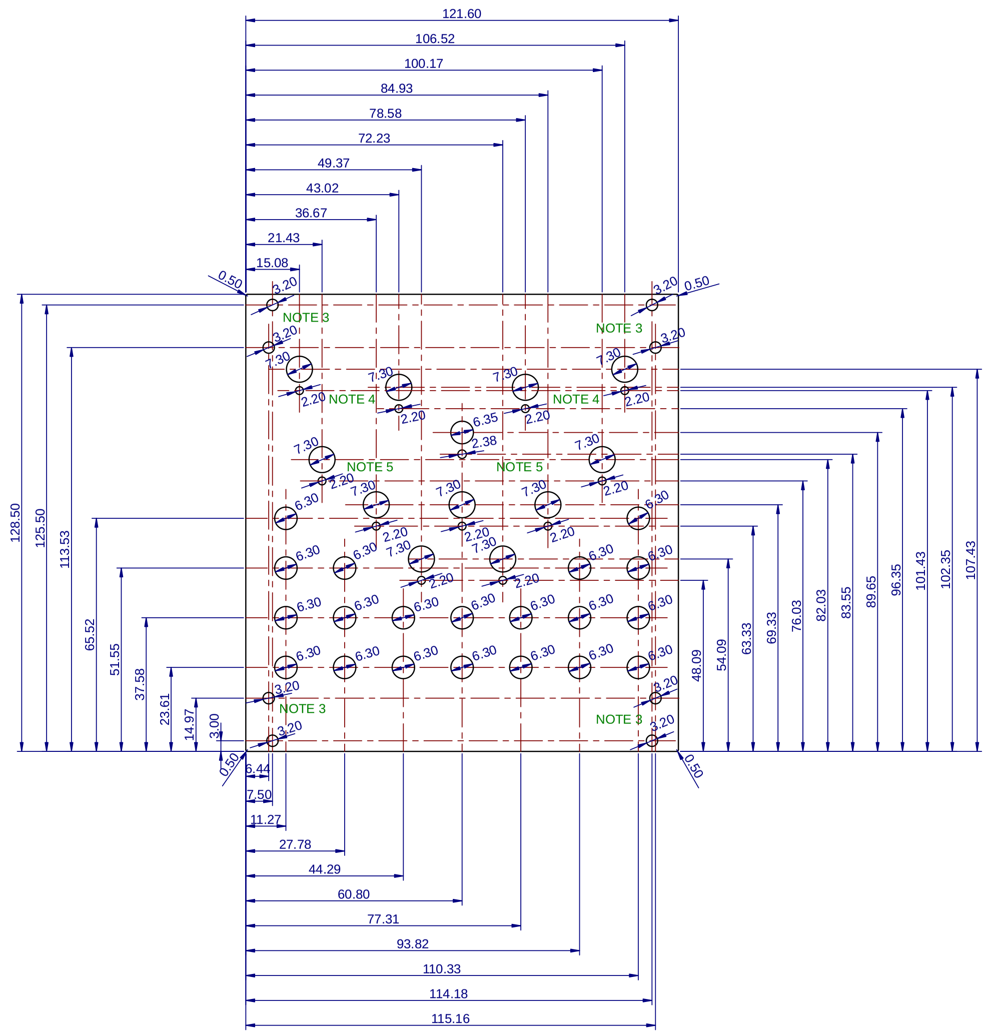

NOTES

1: All dimensions are millimetres with tolerance +/- 0.10mm. Do not scale off drawing.

2: Material is aluminum, 2.00mm thick. Overall dimensions are 128.50mm by 121.60mm, interpolated from Doepfer spec for a 24HP Eurorack synthesizer module.

3: Do not confuse similar horizontal positions. The four 3.20mm holes nearest the top and bottom edges are centred 7.50mm and 114.18mm from the left edge. The other four 3.20mm holes are centred 6.44mm and 115.16mm from the left edge.

4: Do not confuse similar vertical positions. The 2.20mm holes are centred 101.43mm from the bottom edge. The 7.30mm holes are centred 102.35mm from the bottom edge.

5: Do not confuse similar vertical positions. The 7.30mm holes are centred 82.03mm from the bottom edge. The 2.38mm hole is centred 83.55mm from the bottom edge.

MSK 013 Middle Path VCO panel mechanical

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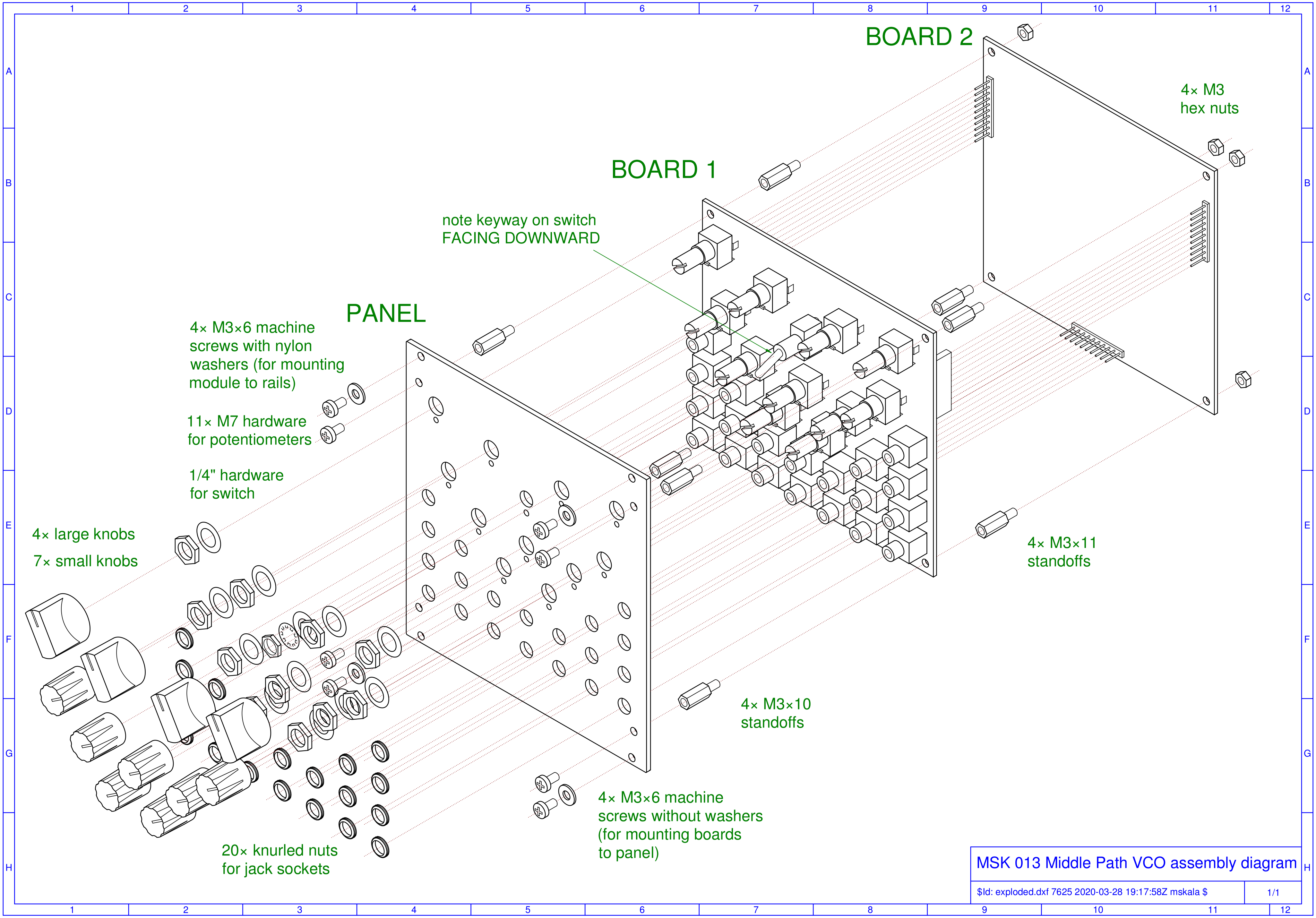

MSK 013 Middle Path VCO assembly diagram

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