MSK 010 Fixed Sine Bank

North Coast Synthesis Ltd.
Matthew Skala

August 6, 2022

Contents

General notes

This manual documents the MSK 010 Fixed Sine Bank, which is a control voltage generator module for use in a Eurorack modular synthesizer. Each module contains eight analog sine oscillators, and the same parts can be assembled into three different variants of the module with different selections of output frequencies, so that with three modules, up to 24 different nominal output frequencies are available.

Specifications

This module has no inputs. The impedance of each output is approximately 1kΩ. The open-circuit output voltage is approximately 10V peak to peak (±5V), but this will vary because of component tolerances and is not a guaranteed specification. There may also be a transient outside the normal output voltage range for about half a cycle time during power-up. Shorting any output to any fixed voltage at or between the power rails, or shorting two outputs to each other, is not recommended but should be harmless to the module; patching the MSK 010's output into some other module's output should be harmless to the MSK 010, though that is also not recommended because it is possible the non-MSK 010 module may be harmed.

Nominal output frequencies range from 16mHz to 16Hz, depending on the build variant selected. The frequencies will vary a few percent due to component tolerances, but should have good to very good temperature stability.

This module (assuming a correct build using the recommended components) is protected against reverse power connection. It will not function with the power reversed, but will not cause or suffer any damage. Some other kinds of power misconnection may possibly be dangerous to the module or the power supply.

Most of the current drawn from the power supply by this module goes to lighting up the LEDs, so the current demand fluctuates with the oscillator outputs. In normal operation, the peak current demand is 40mA from each of the +12V and -12V supplies; the average is a fair bit less, more like 25mA. For a few seconds during power-up it may require a few extra milliamps from the negative supply as the larger timing capacitors charge. Placing a heavy load on the outputs (for instance, with so-called passive modules) will increase the power supply current.

The circuit design can operate on ±15V supplies, for use in non-Eurorack synthesizer formats, assuming all the components used are rated for the increased voltage. There should be no need to change any resistor values or similar, as long as the nominal ±5V output level is acceptable. To achieve a different output level may require some trial and error with the Zener diode voltages; no other components need change.

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 3.90″×1.50″, or 99.06mm×38.10mm. They 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 1. Including 18mm of clearance for the mated power connector, the module should fit in 43mm of depth measured from the back of the front panel.

Component substitutions

You can change the frequencies of the oscillators by substituting different resistance and capacitance values, but there are a few things to be aware of. First, the two frequency-determining resistors and the two frequency-determining capacitors in an oscillator unit, must match. I specified 5% capacitors and 1% resistors. Tolerances worse than these are unlikely to work, and 3% capacitors (or hand-matching wider-tolerance caps to that spec) would be better. I specified plastic film capacitors. Tolerance and leakage issues pretty much rule out electrolytic capacitors; and issues of bad DC behaviour rule out silver mica and ferroelectric (X7R and similar) ceramic capacitors. Using NP0 ceramic capacitors should be fine if you can find them in the proper tolerance, but that will usually mean settling for surface-mount.

If you want very long cycle times, you'll probably be pushing both the capacitors and the resistors to the limit, and then it's a question of how much capacitance you can fit into the physical space (maybe you could go as high as 4.7μF and still fit the caps on the board) and how high an impedance you can use with the op amps. The TL074 chips I use seem to perform very well at 10MΩ without the input bias current throwing off the high-impedance tuned circuit; I don't know how much higher in impedance they can go, but I wouldn't be surprised by at least another factor of ten, with careful attention to board

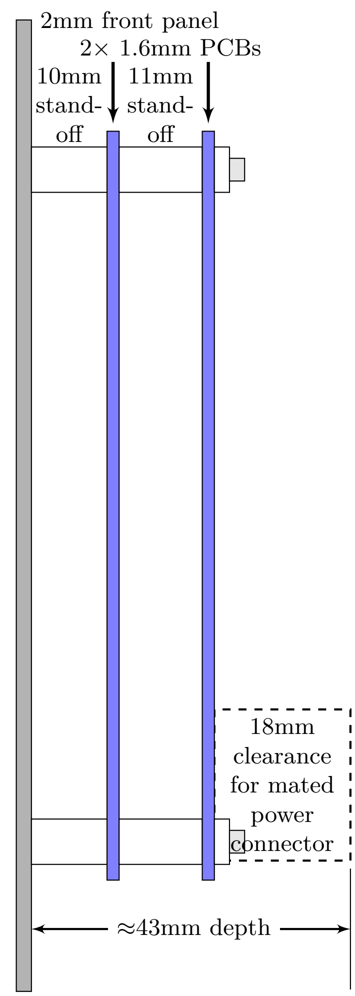


Figure 1: Assembled module, side view.

cleaning and so on. There may be sourcing problems when you try to obtain resistors bigger than 10MΩ in 1% tolerance.

Be aware of the start-up issue: it takes at least a half cycle for each oscillator to settle down into its stable voltage level after power-up, and if you build one with a cycle time of many minutes, that startup time will be noticeable. This is part of the price you pay for having a fully analog implementation; but compare to other analog sine oscillators, such as typical resonating synth filters, which typically have *much longer* startup-time requirements in relation to their cycle times.

Making the frequency adjustable with this circuit would not be easy because of the need to make two variable components vary at once and track each other. The necessary level of matching is at the limits of what an inexpensive dual-gang potentiometer might be able to achieve, and trying to make it voltage controlled too would be even worse. You're probably better off switching to some completely different design if you must have variable frequency.

Swapping out the TL074 op amps for some other model is not recommended. No relevant specification of this circuit would be improved by a "better" op amp, and op amps designed for audio use may lack the very high input impedance of the TL074, which is critically necessary for this circuit (especially in the longer cycle time oscillators).

This circuit's output level is determined by 1N5229B Zener diodes running at significantly less than the 20mA nominal reverse current for which their voltage is officially specified, and as a result, their behaviour may be hard to predict, inconsistent from manufacturer to manufacturer, and so on. I specified these, and the 27kΩ ballast resistors to go with them, after extensive testing with physical samples. If you substitute these diodes, then test the diodes you plan to use carefully to make sure they give the output level you want.

Use and contact information

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, and this module uses impedances into the megaohm range, where the leakage currents may have some effect on circuit operation. 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.

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.	
4	C1, C2, C5, C6	0.10μF	film, 0.2″ lead spacing
4	C9, C10, C19, C20	0.1μF	axial ceramic
4	C11, C12, C15, C16	0.22μF	film, 0.2″ lead spacing
4	C3, C7, C13, C17	0.47μF	film, 0.2″ lead spacing
4	C4, C8, C14, C18	1.0μF	film, 0.2″ lead spacing
2	C21, C22	10μF	radial aluminum electrolytic, 0.1″ lead spacing
16	D1–D8, D13–D20	1N5229B	4.3V Zener
2	D25, D26	1N5818	or SB130; Schottky rectifier
8	D9–D12, D21–D24	L-57EGW	bi-colour LED, Kingbright
2	H4, H8	M3	nut for M3 machine screw
2	H2, H6	M3x10	M3 male-female standoff, 10mm body length
2	H3, H7	M3x11	M3 male-female standoff, 11mm body length
6	H1, H5, H9, H10, H13, H14	M3x6	M3 machine screw, 6mm body length
4	H11, H12, H17, H18	nylon	nylon washer for M3 machine screw
8	J1–J8	1502 03	switched mono 3.5mm panel jack, Lumberg
1	J9		female single-row socket, 10 pins at 0.1″
1	P6		male single-row header, 10 pins at 0.1″
1	P1		male Eurorack power header, 2×5 pins at 0.1″
8	R22, R24, R26, R28, R50, R52, R54, R56	510Ω	
8	R21, R23, R25, R27, R49, R51, R53, R55	1kΩ	
8	R1–R4, R29–R32	10kΩ	
8	R9–R12, R37–R40	22kΩ	
8	R17–R20, R45–R48	27kΩ	
2	R5, R13	100kΩ	

Qty	Ref	Value/Part No.	
2	R33, R41	150kΩ	
2	R36, R44	390kΩ	
2	R34, R42	1.0MΩ	
2	R6, R14	1.2MΩ	
2	R7, R15	1.8MΩ	
2	R35, R43	5.6MΩ	
2	R8, R16	10MΩ	
2	U1, U2	TL074	quad JFET-input op amp

Not listed above, but also needed: one front panel, two circuit boards, two 14-pin DIP sockets for the ICs, solder, and incidental supplies such as alcohol for cleaning.

Fixed resistors should be 1% metal film throughout. Film capacitors should be 5% or better. These tolerances are important to guarantee oscillation. RoHS-certified zinc-plated steel hardware is recommended, not stainless steel because of galvanic-corrosion incompatibility with aluminum parts.

Resistor and capacitor reference designators shown are for the "A" variant of the module; install them in a different arrangement, according to the instructions in the relevant chapters, for other variants.

North Coast Synthesis Ltd. kits or assembled modules sometimes contain other parts with equivalent or better specifications rather than exact manufacturers and part numbers shown here.

Building Board 2 (Variant A)

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. But before you start assembling Board 2, you must decide which variant you want to build. Each one has a different selection of eight nominal output frequencies. Follow the instructions in *one* of the three "Building Board 2" chapters, depending on which variant you want, before proceeding to the chapter called "Building Board 1." It's a choose your own module adventure!

This chapter contains the build instructions for Variant A, which has the following nominal output frequencies and periods:

frequency	period
16mHz	63s
60mHz	16s
190mHz	5.3s
410mHz	2.4s
720mHz	1.4s
1.3Hz	750ms
4.8Hz	210ms
16Hz	63ms

If you have chosen Variant A, use a permanent marker or some enamel paint to fill in the "A" circle at the lower right of the front panel, so that you can easily keep track of which module the one you're building now is, in a system that might someday contain several MSK 010 modules.

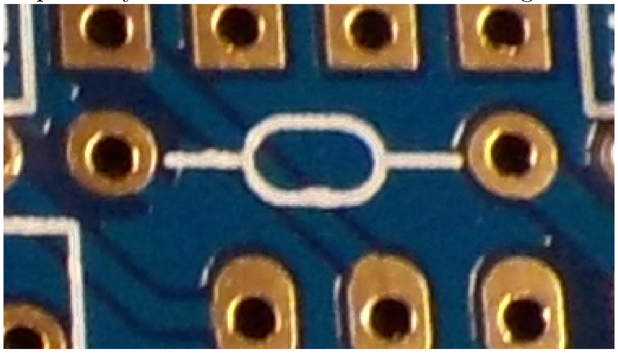
Note that I'm describing a separate step for each component value, and I built one that way in order to take a photo at each step, but if you are reasonably confident about your skills you may find it easier to populate all or most of the board (i.e. put the components in place) and then solder them all at once. Except where noted, the order in which you add components does not matter much; but do note that you should solder the board-to-board connector before the larger capacitors, because otherwise they block access to it.

Preliminaries

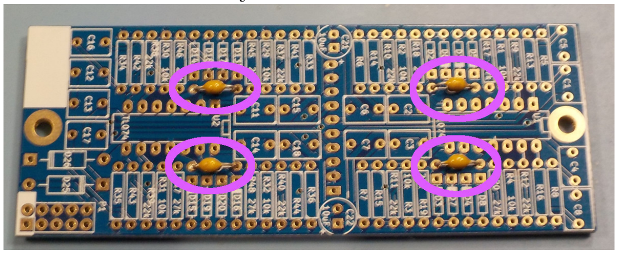
Count out the right number of everything according to the bill of materials. There is an abbreviated BOM for Board 2, and a few items from Board 1 used during the assembly of Board 2, in Table 4.

Decoupling capacitors

The four axial ceramic 0.1μF decoupling capacitors, C9, C10, C19, and C20, are shown on the board by a special symbol without their reference designators.



Install these four 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 op amp chips, reducing any coupling of high-frequency noise between them and the rest of the synthesizer.



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, metal film 1% resistors are recommended for all fixed-value resistors. These will usually have blue bodies and four colour bands designating the value, plus a fifth band

This table is not a substitute for the text instructions.

Qty	Ref	Value/Part No.	
4	C1, C2, C5, C6	0.10μF	film, 0.2$''$ lead spacing
4	C9, C10, C19, C20	0.1μF	axial ceramic
4	C11, C12, C15, C16	0.22μF	film, 0.2$''$ lead spacing
4	C3, C7, C13, C17	0.47μF	film, 0.2$''$ lead spacing
4	C4, C8, C14, C18	1.0μF	film, 0.2$''$ lead spacing
2	C21, C22	10μF	radial aluminum electrolytic, 0.1$''$ lead spacing
16	D1–D8, D13–D20	1N5229B	4.3V Zener
2	D25, D26	1N5818	or SB130; Schottky rectifier
2	H2, H6	M3x10	M3 male-female standoff, 10mm body length
2	H3, H7	M3x11	M3 male-female standoff, 11mm body length
2	H1, H5	M3x6	M3 machine screw, 6mm body length
1	J9		female single-row socket, 10 pins at 0.1$''$
1	P6		male single-row header, 10 pins at 0.1$''$
1	P1		male Eurorack power header, 2×5 pins at 0.1$''$
8	R1–R4, R29–R32	10kΩ	
8	R9–R12, R37–R40	22kΩ	
8	R17–R20, R45–R48	27kΩ	
2	R5, R13	100kΩ	
2	R33, R41	150kΩ	
2	R36, R44	390kΩ	
2	R34, R42	1.0MΩ	
2	R6, R14	1.2MΩ	
2	R7, R15	1.8MΩ	
2	R35, R43	5.6MΩ	
2	R8, R16	10MΩ	
2	U1, U2		14-pin DIP socket

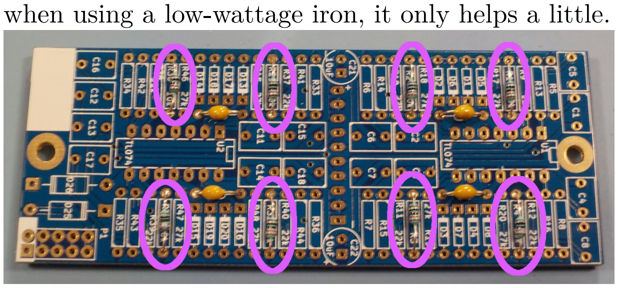
Table 2: Bill of Materials for assembling Board 2.

(always brown*) for the tolerance, and these are the types of resistors shipped in the North Coast kits. 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.

The physical size of the resistors may vary, and details like the exact colour of the bluish background. You can see some of that variation in the photos in these instructions. Some of the resistance values used in this module are hard to find, and we source different values from different suppliers, so not all the resistors in a kit will necessarily be from the same manufacturer, nor match on non-critical specifications like power rating and physical size.

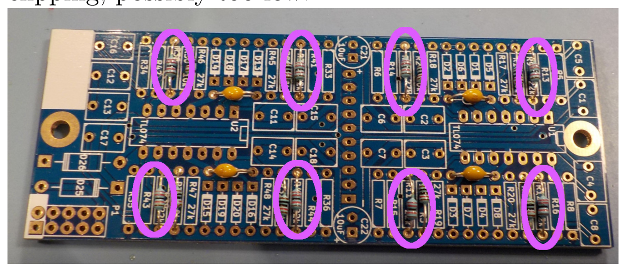
Install the eight 10kΩ (brown-black-black-red) resistors R1 to R4 and R29 to R32. These form part of the gain-control network for the amplifiers, acting as a reference for the other components to balance against. Do not confuse these with similar-looking resistors for other power-of-ten values, such as 1kΩ or 1MΩ; those have the same colour code except with the red replaced by other colours.

Be aware that one leg of each of these resistors is connected to the ground plane of the circuit board, a fact evident from the cross-shaped pattern of "thermal relief" connections around the solder pad. These joints, and other grounded pins throughout the module, may require extra time and heat to solder because each one is connected to large chunks of copper on both sides of the board that tend to conduct heat away from the joint. The thermal relief design is supposed to reduce this effect, but in practice, especially when using a low-wattage iron, it only helps a little.

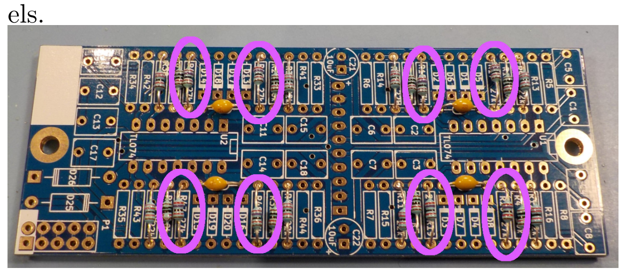


*It also happens, because of the way we choose resistor values, that the third band will be black for all the resistors used in this module and nearly all the resistors used in North Coast modules in general.

Install the eight 22kΩ (red-red-black-red) resistors R9 to R12 and R37 to R40. These set the small-signal gain for the amplifiers by balancing against the 10kΩ resistors. Do not confuse these with the very similar-looking 27kΩ resistors, which have the second band violet instead of red. Swapping the two values will result in bad output levels, most likely too high with clipping, possibly too low.



Install the eight 27kΩ (red-violet-black-red) resistors R17 to R20 and R45 to R48. These are coupled into the circuit under control of the Zener diodes to reduce the gain as needed for the desired output levels.



The next eight resistor values (two of each) are installed in locations on the board marked with reference designators (like "R5") but no values. That is because these are meant to be installed in different locations depending on which variant of the module you are building. The correspondence between locations and values for Variant A is shown in Figure 2. Follow the diagram and these instructions carefully, because it is easy to make a mistake.

All these resistors are used to determine the frequencies of the oscillators, two for each oscillator. Installing the wrong timing resistor value in one of the oscillators, but the same wrong value for both of the two timing resistors, will result in oscillation at the wrong frequency. Installing two different resistor values in one oscillator will probably result in its failure to oscillate at all.

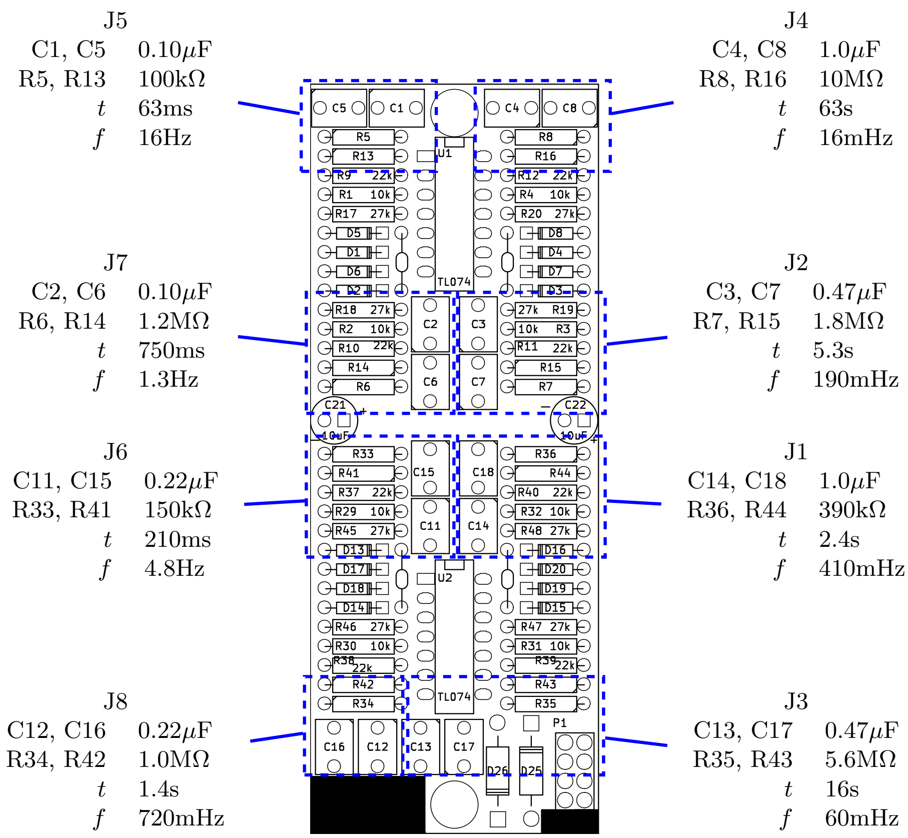
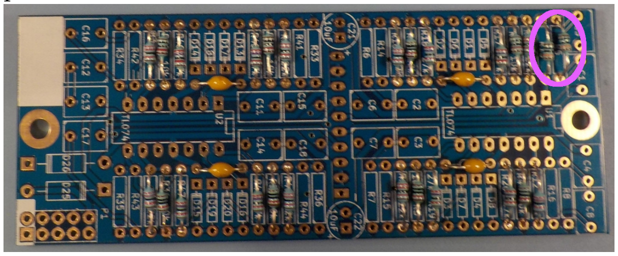
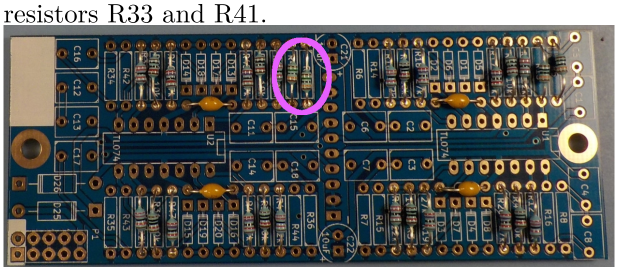


Figure 2: Populating Board 2 for Variant A

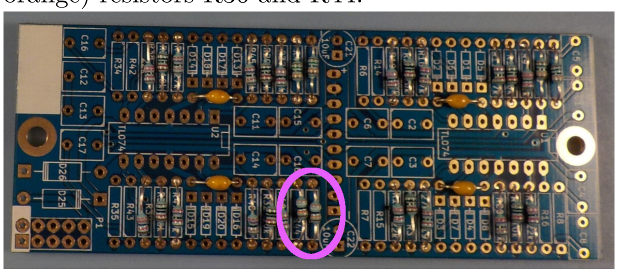
Install the two 100kΩ (brown-black-black-orange) resistors R5 and R13. Do not confuse these with other power-of-ten values.



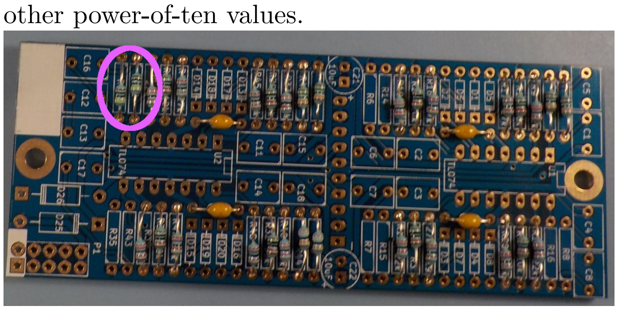
Install the two 150kΩ (brown-green-black-orange) resistors R33 and R41.



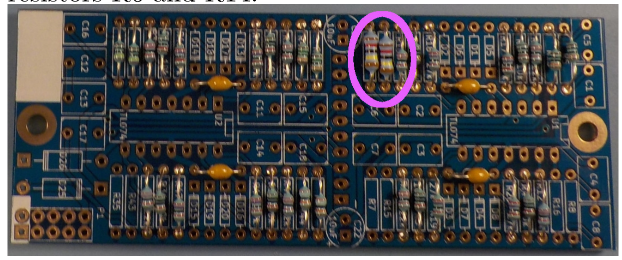
Install the two 390kΩ (orange-white-black-orange) resistors R36 and R44.



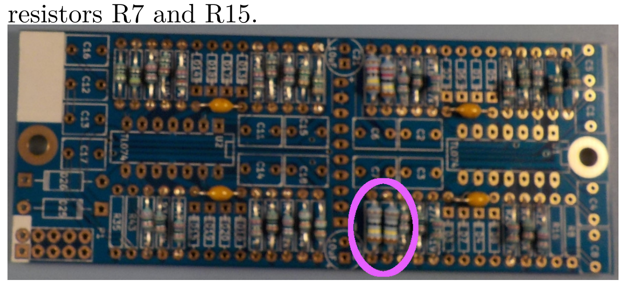
Install the two 1.0MΩ (brown-black-black-yellow) resistors R34 and R42. Do not confuse these with other power-of-ten values.



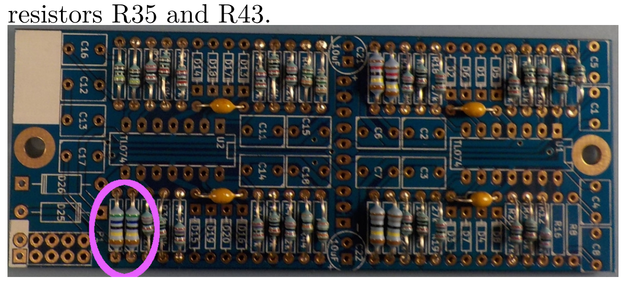
Install the two 1.2MΩ (brown-red-black-yellow) resistors R6 and R14.



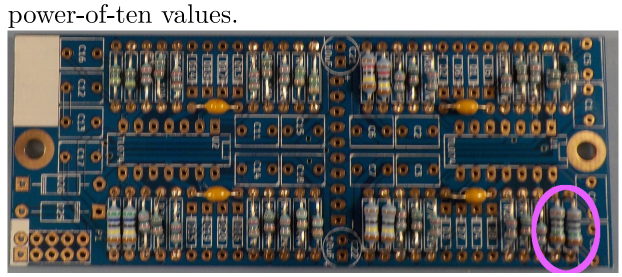
Install the two 1.8MΩ (brown-gray-black-yellow) resistors R7 and R15.



Install the two 5.6MΩ (green-blue-black-yellow) resistors R35 and R43.



Install the two 10MΩ (brown-black-black-green) resistors R8 and R16. Do not confuse these with other power-of-ten values.



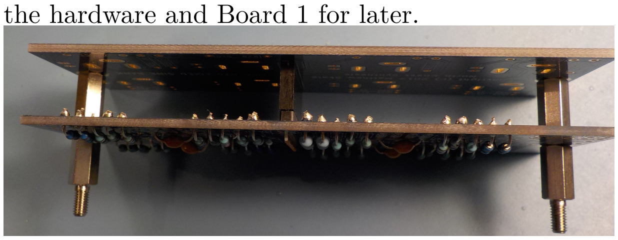
Board to board connectors

It is important to solder the male header connector that links Board 2 to Board 1 at this time, before adding the film and electrolytic capacitors, because the capacitors surround the solder pads on the front of Board 2 in a way that makes it difficult to work on the connector without damaging the capacitors. For best alignment, you should solder the male connector while it is mated with the female connector on

Board 1, and it's convenient to solder the Board 1 connector at this time too.

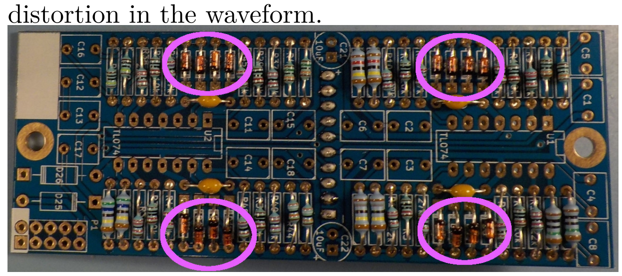
It is important to solder the connectors to the correct side of each board. Every component has a silkscreen marking on the board and the body of the component should be assembled on the side where the silkscreen is; normally you would then apply solder on the opposite side, where the legs poke through and there is no silkscreen marking. The body of the male connector P6 should be on the side *opposite* the resistors and other components already installed on Board 2. It is the only component on its side of the board. The body of the female connector J9 should be on *the same side* as the places where the resistors are marked for installation on Board 1, and opposite the side where the jack sockets and LEDs are marked for installation. See the photo below and the exploded diagram at the end of this manual.

Assemble the two boards and the two connectors using the M3 machine screws, and 10mm and 11mm standoffs, as shown. The 11mm standoffs should separate the two boards; I suggest using the 10mm standoffs instead of hex nuts for this temporary assembly because they're easier to tighten by hand. Do not confuse the two lengths. Solder the connectors on both boards. Then disassemble them, and set aside the hardware and Board 1 for later.



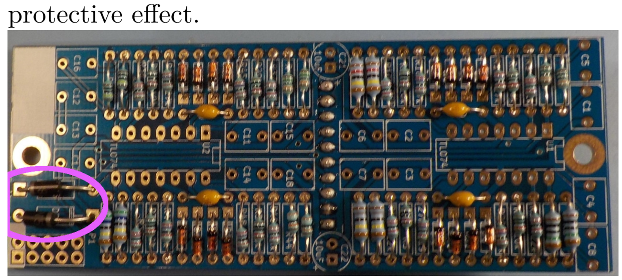
Semiconductors

Install the sixteen 1N5229B 4.3V Zener diodes D1 to D8 and D13 to D20. These control the output level of the oscillators, by gradually bringing the 27kΩ resistors into the circuit as the level increases to back down the gain until it reaches equilibrium. They are polarized components and it is important to install them right way round. Each diode is packaged inside a pink glass bead with a black 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; and the diodes are arranged so that all the cathodes point inward from the edge of the board. Installing one of these diodes backwards will probably result in the output level of the corresponding oscillator being much too low, as well as some asymmetric (second harmonic) distortion in the waveform.



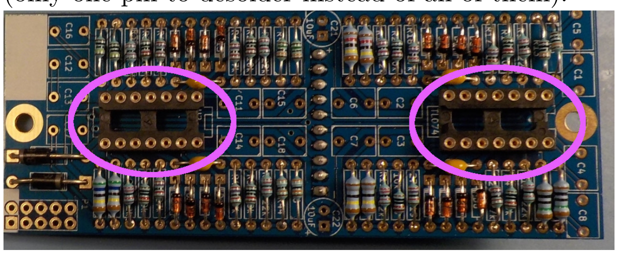
The 1N5229B diodes are the only small glass diodes in an MSK 010 kit, but be warned that if you're doing other electronic construction, then you will probably have many other small glass diodes on hand (for instance, the very popular 1N4148 general-purpose type) and they all look pretty much identical, distinguished only by their electrical properties and near-microscopic code numbers etched onto the glass. Be careful not to mix these diodes up with other types of diodes. Substituting general-purpose switching diodes in this circuit will probably give you output levels that are much too high.

Install the two 1N5818 or SBA130 Schottky rectifier diodes D25 and D26. These are for reverse-voltage protection; they cut off power to the module when the power plug is backwards. They are polarized and it is important to install them in the right direction. As with the Zeners, these diodes will be marked with stripes indicating their cathodes (here, probably white or light grey paint on a black or dark grey plastic package) and those stripes should match the stripes on the PCB silkscreen. The cathode solder pads are also square. Installing these backwards means they will have the opposite of the intended protective effect.



Install the two 14-pin DIP sockets for the TL074 quad op amp chips, U1 and U2. These chips provide amplification to keep the oscillators running. The 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, 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.

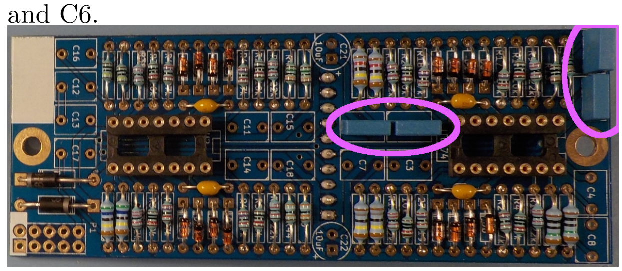
Film capacitors

The film capacitors in this module are used to determine oscillator timing. As with the timing resistors, they are marked on the PCB with their references only, no capacitance values, because they are arranged differently for the different module variants. See Figure 2 for information on which capacitors go where in this variant.

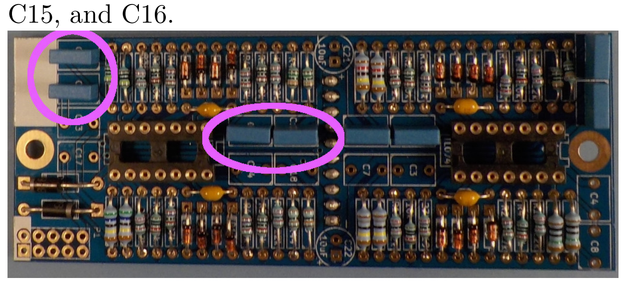
Be careful to identify the values of the capacitors correctly. They may all look very similar. In some cases the physical sizes of the capacitors vary with their value (for instance, 1.0μF will probably be bigger than 0.1μF), but there may also be different values the same physical size. Etched markings on the capacitors will probably use the symbol μ instead of a decimal point, such as μ1 to designate 0.1μF, as opposed to 1μ for 1.0μF. Many digital multimeters will have a "capacitor test" feature which you can use to confirm that you've identified the capacitors correctly. Installing the wrong capacitors in an oscillator will give you the wrong frequency (in case of two capacitors that are the same wrong value) or no oscillation (in case of two capacitors of different values).

Also be careful about the physical aspects of installing the capacitors. I usually stick them in place with vinyl tape before soldering, but it's difficult to get them to stay in at a nice angle. If they're tilted over, that is only really a cosmetic issue; the circuit should work fine as long as both electrical connections are made. These capacitors are also unpolarized, and will work electrically regardless of the direction in which they are installed.

Install the four 0.1μF film capacitors C1, C2, C5, and C6.

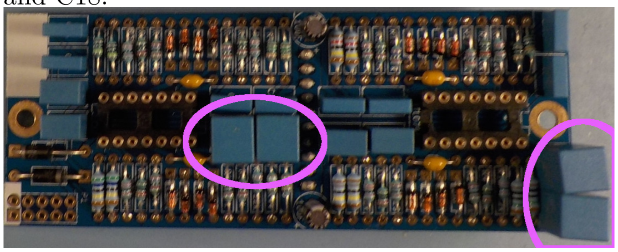


Install the four 0.22μF film capacitors C11, C12, C15, and C16.



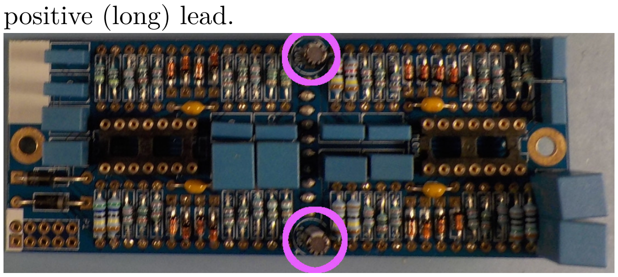
Install the four 0.47μF film capacitors C3, C7, C13, and C17.

Install the four 1.0μF film capacitors C4, C8, C14, and C18.[†]



Electrolytic capacitors

Install the two 10μF electrolytic capacitors C21 and C22, 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.

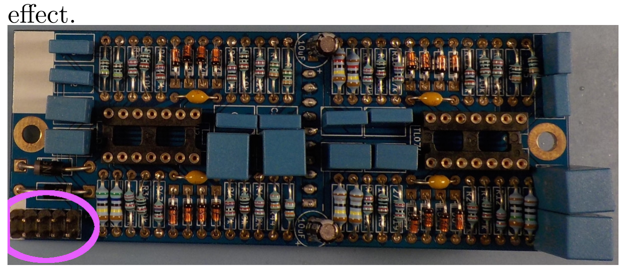


Eurorack power connector

Install the 2×5-pin Eurorack power connector. This connector is not polarized in itself, although the connection it makes is polarized. As with the DIP sockets, you should be careful to get it installed snugly against the board, not tilted at an angle. Use vinyl tape or similar to hold it in place, solder one pin, then check that it is straight before you solder the other pins.

Be aware that both the connector and the copper connections to it on the PCB have relatively large thermal mass. These solder joints will need more heat than usual; and after you have soldered it, the connector will remain hot longer than recently-soldered components usually do. Don't burn yourself.

The six pins in the centre of the connector, that is all except the four corner pins, are for grounding and they are all connected together on the board. Thus, if you accidentally form solder bridges among these six pins while installing the connector, don't waste effort trying to remove them; they will have no electrical effect.



That's all the components for Board 2.

Because some connections on this board operate at multi-megaohm impedances, it may be a good idea to clean the flux residue off of Board 2 even if you are using no-clean flux which would not normally require cleaning. For this type of solder flux, or traditional rosin, use isopropyl alcohol for cleaning. If you used water-soluble solder flux, then cleaning is mandatory and you should use water.

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

[†]This photo shows the 10μF capacitors already installed, but that's really the next step.

Building Board 2 (Variant B)

This chapter contains the build instructions for Variant B, which has the following nominal output frequencies and periods:

frequency	period
34mHz	30s
88mHz	11s
160mHz	6.3s
280mHz	3.5s
600mHz	1.6s
1.8Hz	540ms
3.4Hz	300ms
11Hz	94ms

If you have chosen Variant B, use a permanent marker or some enamel paint to fill in the "B" circle at the lower right of the front panel, so that you can easily keep track of which module the one you're building now is, in a system that might someday contain several MSK 010 modules.

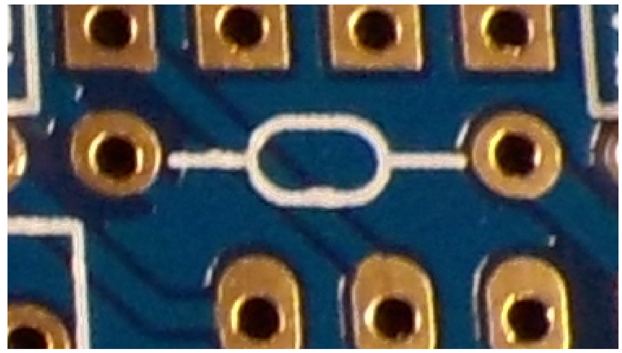
Note that I'm describing a separate step for each component value, and I built one that way in order to take a photo at each step, but if you are reasonably confident about your skills you may find it easier to populate all or most of the board (i.e. put the components in place) and then solder them all at once. Except where noted, the order in which you add components does not matter much; but do note that you should solder the board-to-board connector before the larger capacitors, because otherwise they block access to it.

Preliminaries

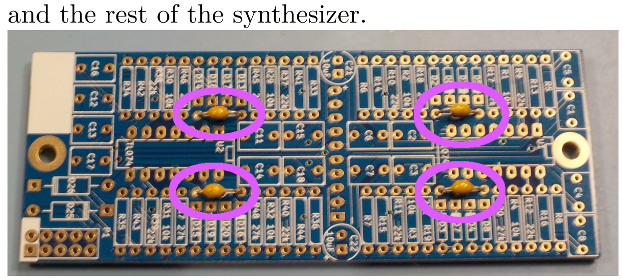
Count out the right number of everything according to the bill of materials. There is an abbreviated BOM for Board 2, and a few items from Board 1 used during the assembly of Board 2, in Table 4.

Decoupling capacitors

The four axial ceramic 0.1μF decoupling capacitors, C9, C10, C19, and C20, are shown on the board by a special symbol without their reference designators.



Install these four 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 op amp chips, reducing any coupling of high-frequency noise between them and the rest of the synthesizer.



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, metal film 1% resistors are recommended for all fixed-value resistors. These will usually have blue bodies and four colour bands designating the value, plus a fifth band (always brown*) for the tolerance, and these are the types of resistors shipped in the North Coast kits. 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

*It also happens, because of the way we choose resistor values, that the third band will be black for all the resistors used in this module and nearly all the resistors used in North Coast modules in general.

This table is not a substitute for the text instructions.

Qty	Ref	Value/Part No.	
4	C1, C5, C14, C18	0.10μF	film, 0.2″ lead spacing
4	C9, C10, C19, C20	0.1μF	axial ceramic
4	C2, C6, C12, C16	0.22μF	film, 0.2″ lead spacing
4	C4, C8, C11, C15	0.47μF	film, 0.2″ lead spacing
4	C3, C7, C13, C17	1.0μF	film, 0.2″ lead spacing
2	C21, C22	10μF	radial aluminum electrolytic, 0.1″ lead spacing
16	D1–D8, D13–D20	1N5229B	4.3V Zener
2	D25, D26	1N5818	or SB130; Schottky rectifier
2	H2, H6	M3x10	M3 male-female standoff, 10mm body length
2	H3, H7	M3x11	M3 male-female standoff, 11mm body length
2	H1, H5	M3x6	M3 machine screw, 6mm body length
1	J9		female single-row socket, 10 pins at 0.1″
1	P6		male single-row header, 10 pins at 0.1″
1	P1		male Eurorack power header, 2×5 pins at 0.1″
8	R1–R4, R29–R32	10kΩ	
8	R9–R12, R37–R40	22kΩ	
8	R17–R20, R45–R48	27kΩ	
2	R33, R41	100kΩ	
2	R5, R13	150kΩ	
2	R6, R14	390kΩ	
2	R7, R15	1.0MΩ	
2	R34, R42	1.2MΩ	
2	R35, R43	1.8MΩ	
2	R36, R44	5.6MΩ	
2	R8, R16	10MΩ	
2	U1, U2		14-pin DIP socket

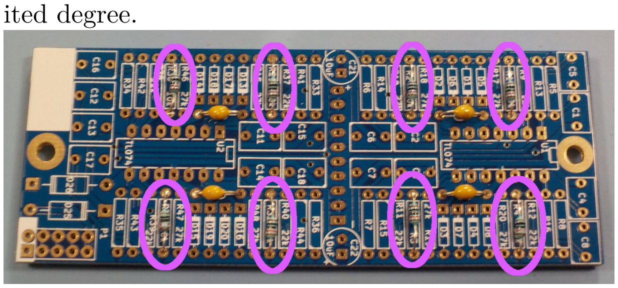
Table 3: Bill of Materials for assembling Board 2.

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.

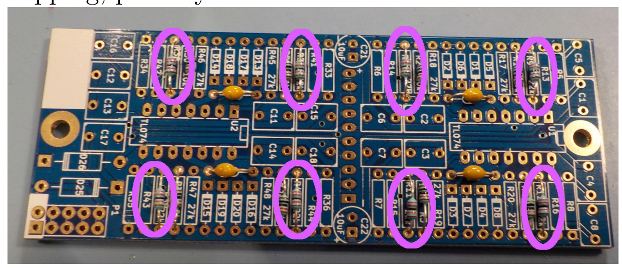
The physical size of the resistors may vary, and details like the exact colour of the bluish background. You can see some of that variation in the photos in these instructions. Some of the resistance values used in this module are hard to find, and we source different values from different suppliers, so not all the resistors in a kit will necessarily be from the same manufacturer, nor match on non-critical specifications like power rating and physical size.

Install the eight 10kΩ (brown-black-black-red) resistors R1 to R4 and R29 to R32. These form part of the gain-control network for the amplifiers, acting as a reference for the other components to balance against. Do not confuse these with similar-looking resistors for other power-of-ten values, such as 1kΩ or 1MΩ; those have the same colour code except with the red replaced by other colours.

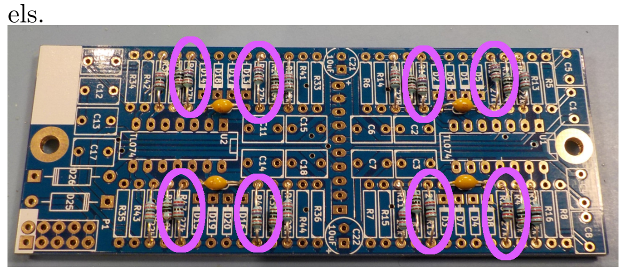
Be aware that one leg of each of these resistors is connected to the ground plane of the circuit board, a fact evident from the cross-shaped pattern of "thermal relief" connections around the solder pad. These joints, and other grounded pins throughout the module, may require extra time and heat to solder because each one is connected to large chunks of copper on both sides of the board that tend to conduct heat away from the joint. The thermal relief design is supposed to reduce this effect, but in practice, especially when using a low-wattage iron, it only helps to a limited degree.



Install the eight 22kΩ (red-red-black-red) resistors R9 to R12 and R37 to R40. These set the small-signal gain for the amplifiers by balancing against the 10kΩ resistors. Do not confuse these with the very similar-looking 27kΩ resistors, which have the second band violet instead of red. Swapping the two values will result in bad output levels, most likely too high with clipping, possibly too low.



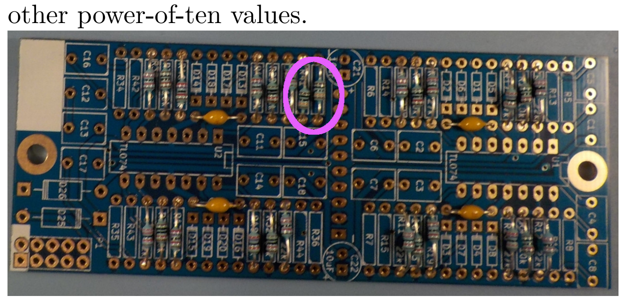
Install the eight 27kΩ (red-violet-black-red) resistors R17 to R20 and R45 to R48. These are coupled into the circuit under control of the Zener diodes to reduce the gain as needed for the desired output levels.



The next eight resistor values (two of each) are installed in locations on the board marked with reference designators (like "R5") but no values. That is because these are meant to be installed in different locations depending on which variant of the module you are building. The correspondence between locations and values for Variant A is shown in Figure 3. Follow the diagram and these instructions carefully, because it is easy to make a mistake.

All these resistors are used to determine the frequencies of the oscillators, two for each oscillator. Installing the wrong timing resistor value in one of the oscillators, but the same wrong value for both of the two timing resistors, will result in oscillation at the wrong frequency. Installing two different resistor values in one oscillator will probably result in its failure to oscillate at all.

Install the two 100kΩ (brown-black-black-orange) resistors R33 and R41. Do not confuse these with other power-of-ten values.



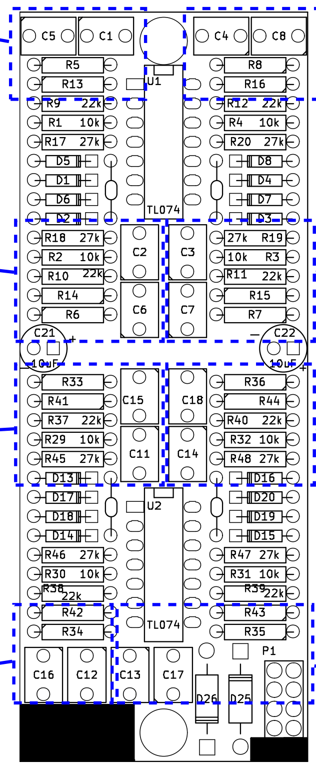
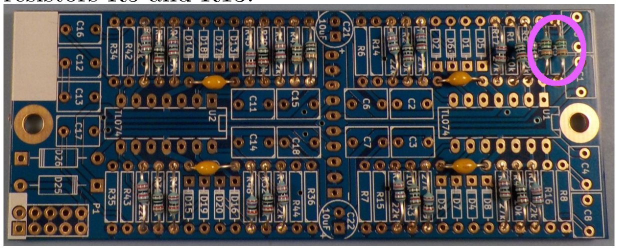
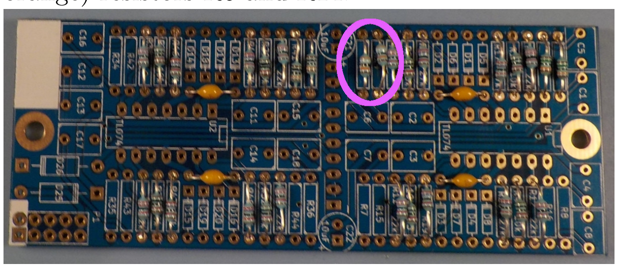


Figure 3: Populating Board 2 for variant B

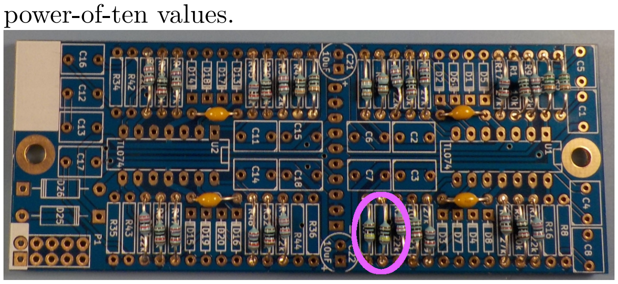
Install the two 150kΩ (brown-green-black-orange) resistors R5 and R13.



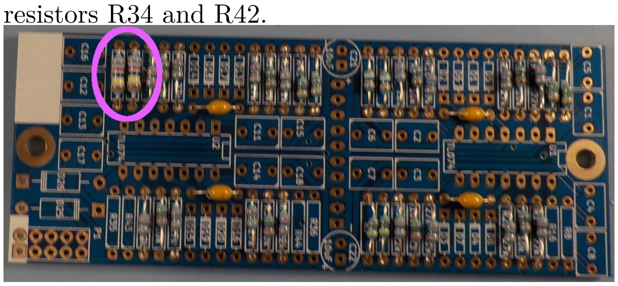
Install the two 390kΩ (orange-white-black-orange) resistors R6 and R14.



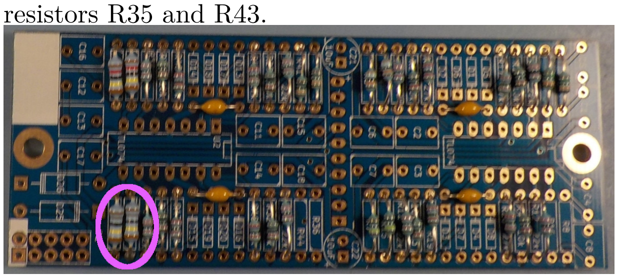
Install the two 1.0MΩ (brown-black-black-yellow) resistors R7 and R15. Do not confuse these with other power-of-ten values.



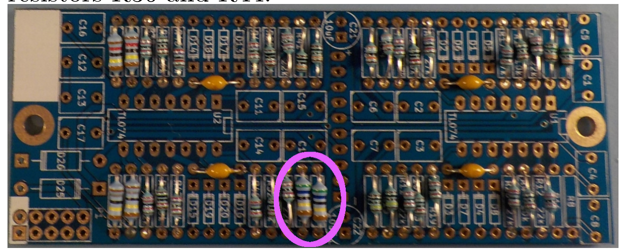
Install the two 1.2MΩ (brown-red-black-yellow) resistors R34 and R42.



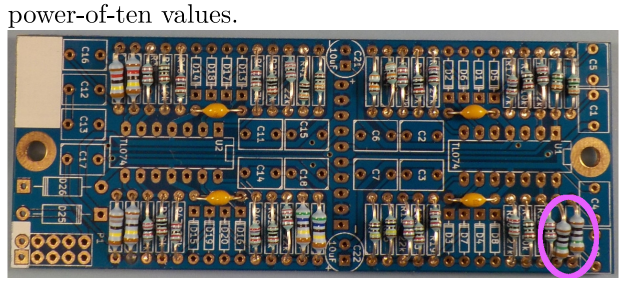
Install the two 1.8MΩ (brown-gray-black-yellow) resistors R35 and R43.



Install the two 5.6MΩ (green-blue-black-yellow) resistors R36 and R44.



Install the two 10MΩ (brown-black-black-green) resistors R8 and R16. Do not confuse these with other power-of-ten values.



Board to board connectors

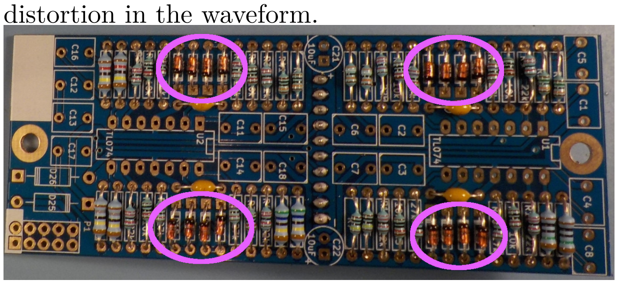
It is important to solder the male header connector that links Board 2 to Board 1 at this time, before adding the film and electrolytic capacitors, because the capacitors surround the solder pads on the front of Board 2 in a way that makes it difficult to work on the connector without damaging the capacitors. For best alignment, you should solder the male connector while it is mated with the female connector on Board 1, and it's convenient to solder the Board 1 connector at this time too.

It is important to solder the connectors to the correct side of each board. Every component has a silkscreen marking on the board and the body of the component should be assembled on the side where the silkscreen is; normally you would then apply solder on the opposite side, where the legs poke through and there is no silkscreen marking. The body of the male connector P6 should be on the side *opposite* the resistors and other components already installed on Board 2. It is the only component on its side of the board. The body of the female connector J9 should be on *the same side* as the places where the resistors are marked for installation on Board 1, and opposite the side where the jack sockets and LEDs are marked for installation. See the photo below and the exploded diagram at the end of this manual.

Assemble the two boards and the two connectors using the M3 machine screws, and 10mm and 11mm standoffs, as shown. The 11mm standoffs should separate the two boards; I suggest using the 10mm standoffs instead of hex nuts for this temporary assembly because they're easier to tighten by hand. Do not confuse the two lengths. Solder the connectors on both boards. Then disassemble them, and set aside the hardware and Board 1 for later.

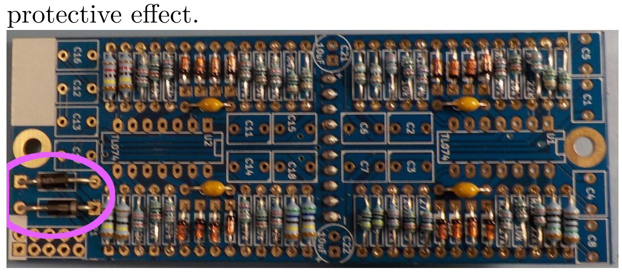
Semiconductors

Install the sixteen 1N5229B 4.3V Zener diodes D1 to D8 and D13 to D20. These control the output level of the oscillators, by gradually bringing the 27kΩ resistors into the circuit as the level increases to back down the gain until it reaches equilibrium. They are polarized components and it is important to install them right way round. Each diode is packaged inside a pink glass bead with a black 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; and the diodes are arranged so that all the cathodes point inward from the edge of the board. Installing one of these diodes backwards will probably result in the output level of the corresponding oscillator being much too low, as well as some asymmetric (second harmonic) distortion in the waveform.



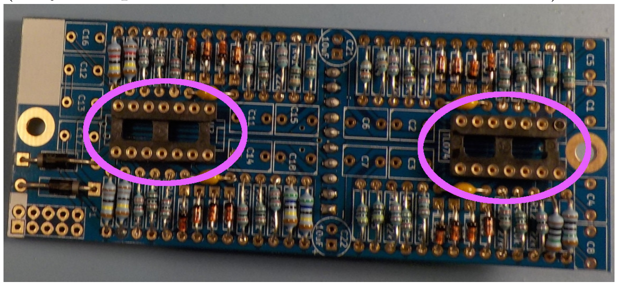
The 1N5229B diodes are the only small glass diodes in an MSK 010 kit, but be warned that if you're doing other electronic construction, then you will probably have many other small glass diodes on hand (for instance, the very popular 1N4148 general-purpose type) and they all look pretty much identical, distinguished only by their electrical properties and near-microscopic code numbers etched onto the glass. Be careful not to mix these diodes up with other types of diodes. Substituting general-purpose switching diodes in this circuit will probably give you output levels that are much too high.

Install the two 1N5818 or SBA130 Schottky rectifier diodes D25 and D26. These are for reverse-voltage protection; they cut off power to the module when the power plug is backwards. They are polarized and it is important to install them in the right direction. As with the Zeners, these diodes will be marked with stripes indicating their cathodes (here, probably white or light grey paint on a black or dark grey plastic package) and those stripes should match the stripes on the PCB silkscreen. The cathode solder pads are also square. Installing these backwards means they will have the opposite of the intended protective effect.



Install the two 14-pin DIP sockets for the TL074 quad op amp chips, U1 and U2. These chips provide amplification to keep the oscillators running. The 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, 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.

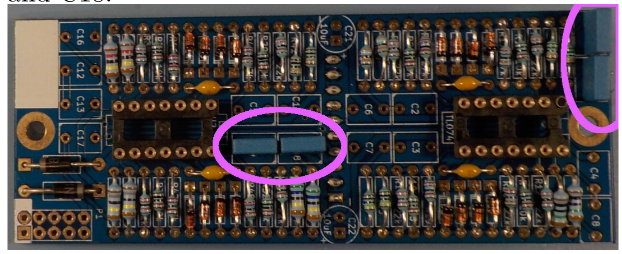
Film capacitors

The film capacitors in this module are used to determine oscillator timing. As with the timing resistors, they are marked on the PCB with their references only, no capacitance values, because they are arranged differently for the different module variants. See Figure 3 for information on which capacitors go where in this variant.

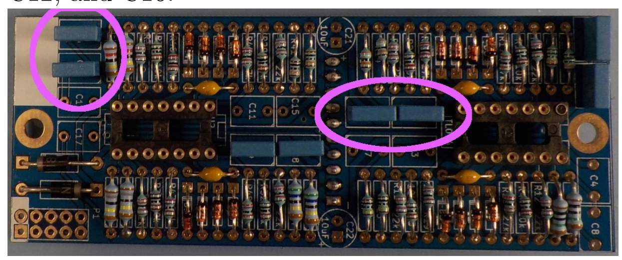
Be careful to identify the values of the capacitors correctly. They may all look very similar. In some cases the physical sizes of the capacitors vary with their value (for instance, 1.0μF will probably be bigger than 0.1μF), but there may also be different values the same physical size. Etched markings on the capacitors will probably use the symbol μ instead of a decimal point, such as μ1 to designate 0.1μF, as opposed to 1μ for 1.0μF. Many digital multimeters will have a "capacitor test" feature which you can use to confirm that you've identified the capacitors correctly. Installing the wrong capacitors in an oscillator will give you the wrong frequency (in case of two capacitors that are the same wrong value) or no oscillation (in case of two capacitors of different values).

Also be careful about the physical aspects of installing the capacitors. I usually stick them in place with vinyl tape before soldering, but it's difficult to get them to stay in at a nice angle. If they're tilted over, that is only really a cosmetic issue; the circuit should work fine as long as both electrical connections are made. These capacitors are also unpolarized, and will work electrically regardless of the direction in which they are installed.

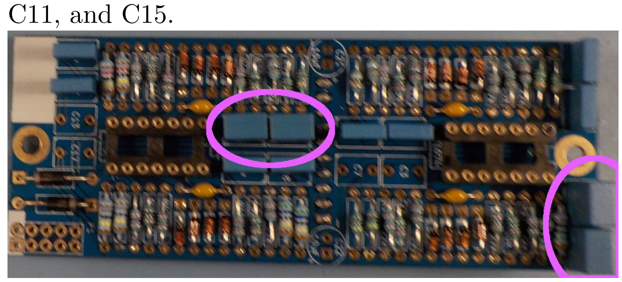
Install the four 0.1μF film capacitors C1, C5, C14, and C18.



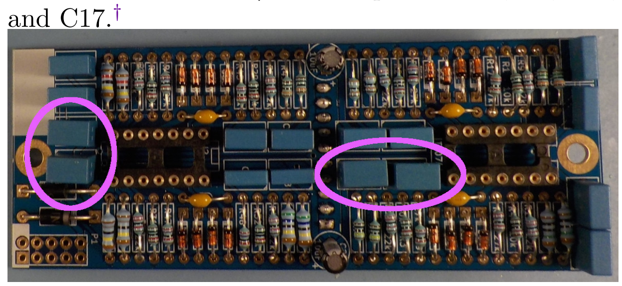
Install the four 0.22μF film capacitors C2, C6, C12, and C16.



Install the four 0.47μF film capacitors C4, C8, C11, and C15.



Install the four 1.0μF film capacitors C3, C7, C13, and C17.[†]

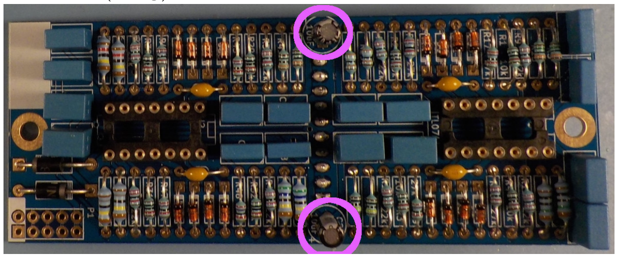


Electrolytic capacitors

Install the two 10μF electrolytic capacitors C21 and C22, 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

[†]This photo shows the 10μF capacitors already installed, but that's really the next step.

with the markings on the PCB: plus and minus symbols in the silkscreen and a square solder pad for the positive (long) lead.

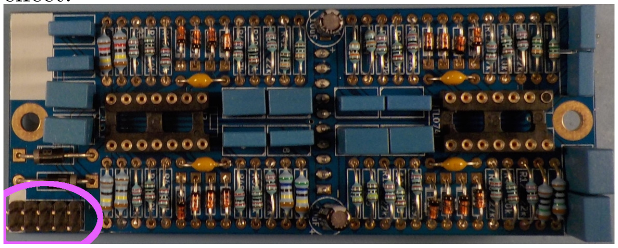


Eurorack power connector

Install the 2×5-pin Eurorack power connector. This connector is not polarized in itself, although the connection it makes is polarized. As with the DIP sockets, you should be careful to get it installed snugly against the board, not tilted at an angle. Use vinyl tape or similar to hold it in place, solder one pin, then check that it is straight before you solder the other pins.

Be aware that both the connector and the copper connections to it on the PCB have relatively large thermal mass. These solder joints will need more heat than usual; and after you have soldered it, the connector will remain hot longer than recently-soldered components usually do. Don't burn yourself.

The six pins in the centre of the connector, that is all except the four corner pins, are for grounding and they are all connected together on the board. Thus, if you accidentally form solder bridges among these six pins while installing the connector, don't waste effort trying to remove them; they will have no electrical effect.



That's all the components for Board 2.

Because some connections on this board operate at multi-megaohm impedances, it may be a good idea to clean the flux residue off of Board 2 even if you are using no-clean flux which would not normally require cleaning. For this type of solder flux, or traditional rosin, use isopropyl alcohol for cleaning. If you used water-soluble solder flux, then cleaning is mandatory and you should use water.

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

Building Board 2 (Variant C)

This chapter contains the build instructions for Variant C, which has the following nominal output frequencies and periods:

frequency	period
28mHz	35s
72mHz	14s
130mHz	7.5s
340mHz	3.0s
880mHz	1.1s
2.2Hz	440ms
4.1Hz	240ms
7.2Hz	140ms

If you have chosen Variant C, use a permanent marker or some enamel paint to fill in the "C" circle at the lower right of the front panel, so that you can easily keep track of which module the one you're building now is, in a system that might someday contain several MSK 010 modules.

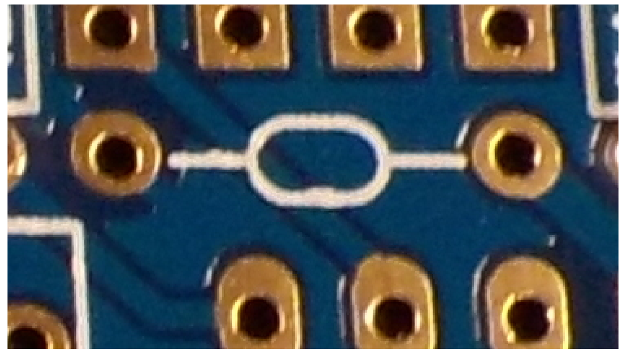
Note that I'm describing a separate step for each component value, and I built one that way in order to take a photo at each step, but if you are reasonably confident about your skills you may find it easier to populate all or most of the board (i.e. put the components in place) and then solder them all at once. Except where noted, the order in which you add components does not matter much; but do note that you should solder the board-to-board connector before the larger capacitors, because otherwise they block access to it.

Preliminaries

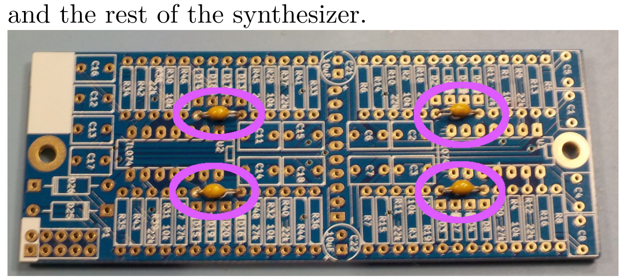
Count out the right number of everything according to the bill of materials. There is an abbreviated BOM for Board 2, and a few items from Board 1 used during the assembly of Board 2, in Table 4.

Decoupling capacitors

The four axial ceramic 0.1μF decoupling capacitors, C9, C10, C19, and C20, are shown on the board by a special symbol without their reference designators.



Install these four 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 op amp chips, reducing any coupling of high-frequency noise between them and the rest of the synthesizer.



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, metal film 1% resistors are recommended for all fixed-value resistors. These will usually have blue bodies and four colour bands designating the value, plus a fifth band (always brown*) for the tolerance, and these are the types of resistors shipped in the North Coast kits. 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

*It also happens, because of the way we choose resistor values, that the third band will be black for all the resistors used in this module and nearly all the resistors used in North Coast modules in general.

This table is not a substitute for the text instructions.

Qty	Ref	Value/Part No.	
4	C11, C12, C15, C16	0.10μF	film, 0.2″ lead spacing
4	C9, C10, C19, C20	0.1μF	axial ceramic
4	C1, C5, C13, C17	0.22μF	film, 0.2″ lead spacing
4	C2, C6, C14, C18	0.47μF	film, 0.2″ lead spacing
4	C3, C4, C7, C8	1.0μF	film, 0.2″ lead spacing
2	C21, C22	10μF	radial aluminum electrolytic, 0.1″ lead spacing
16	D1–D8, D13–D20	1N5229B	4.3V Zener
2	D25, D26	1N5818	or SB130; Schottky rectifier
2	H2, H6	M3x10	M3 male-female standoff, 10mm body length
2	H3, H7	M3x11	M3 male-female standoff, 11mm body length
2	H1, H5	M3x6	M3 machine screw, 6mm body length
1	J9		female single-row socket, 10 pins at 0.1″
1	P6		male single-row header, 10 pins at 0.1″
1	P1		male Eurorack power header, 2×5 pins at 0.1″
8	R1–R4, R29–R32	10kΩ	
8	R9–R12, R37–R40	22kΩ	
8	R17–R20, R45–R48	27kΩ	
2	R5, R13	100kΩ	
2	R6, R14	150kΩ	
2	R33, R41	390kΩ	
2	R36, R44	1.0MΩ	
2	R7, R15	1.2MΩ	
2	R34, R42	1.8MΩ	
2	R8, R16	5.6MΩ	
2	R35, R43	10MΩ	
2	U1, U2		14-pin DIP socket

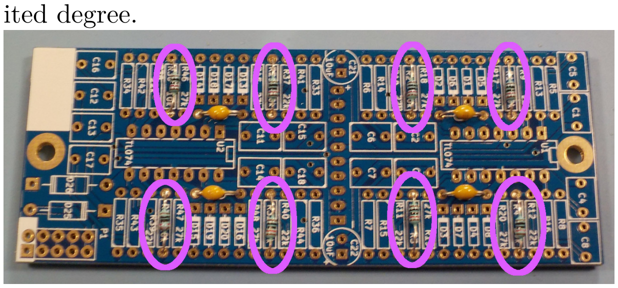
Table 4: Bill of Materials for assembling Board 2.

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.

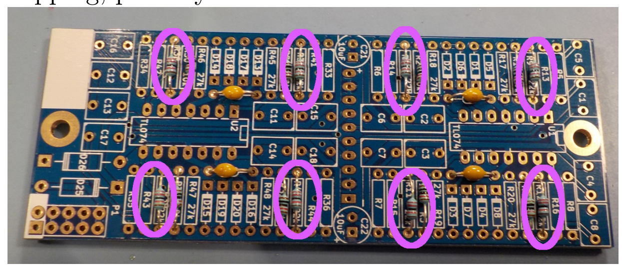
The physical size of the resistors may vary, and details like the exact colour of the bluish background. You can see some of that variation in the photos in these instructions. Some of the resistance values used in this module are hard to find, and we source different values from different suppliers, so not all the resistors in a kit will necessarily be from the same manufacturer, nor match on non-critical specifications like power rating and physical size.

Install the eight 10kΩ (brown-black-black-red) resistors R1 to R4 and R29 to R32. These form part of the gain-control network for the amplifiers, acting as a reference for the other components to balance against. Do not confuse these with similar-looking resistors for other power-of-ten values, such as 1kΩ or 1MΩ; those have the same colour code except with the red replaced by other colours.

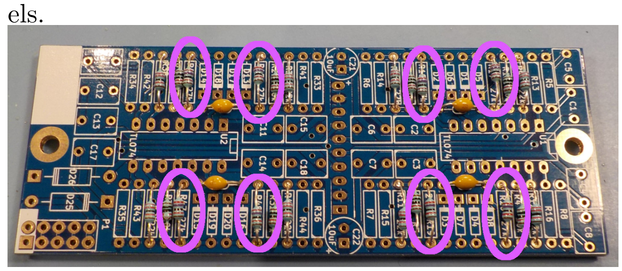
Be aware that one leg of each of these resistors is connected to the ground plane of the circuit board, a fact evident from the cross-shaped pattern of "thermal relief" connections around the solder pad. These joints, and other grounded pins throughout the module, may require extra time and heat to solder because each one is connected to large chunks of copper on both sides of the board that tend to conduct heat away from the joint. The thermal relief design is supposed to reduce this effect, but in practice, especially when using a low-wattage iron, it only helps to a limited degree.



Install the eight 22kΩ (red-red-black-red) resistors R9 to R12 and R37 to R40. These set the small-signal gain for the amplifiers by balancing against the 10kΩ resistors. Do not confuse these with the very similar-looking 27kΩ resistors, which have the second band violet instead of red. Swapping the two values will result in bad output levels, most likely too high with clipping, possibly too low.



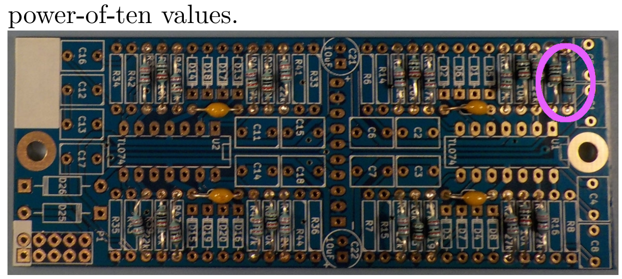
Install the eight 27kΩ (red-violet-black-red) resistors R17 to R20 and R45 to R48. These are coupled into the circuit under control of the Zener diodes to reduce the gain as needed for the desired output levels.



The next eight resistor values (two of each) are installed in locations on the board marked with reference designators (like "R5") but no values. That is because these are meant to be installed in different locations depending on which variant of the module you are building. The correspondence between locations and values for Variant A is shown in Figure 3. Follow the diagram and these instructions carefully, because it is easy to make a mistake.

All these resistors are used to determine the frequencies of the oscillators, two for each oscillator. Installing the wrong timing resistor value in one of the oscillators, but the same wrong value for both of the two timing resistors, will result in oscillation at the wrong frequency. Installing two different resistor values in one oscillator will probably result in its failure to oscillate at all.

Install the two 100kΩ (brown-black-black-orange) resistors R5 and R13. Do not confuse these with other power-of-ten values.



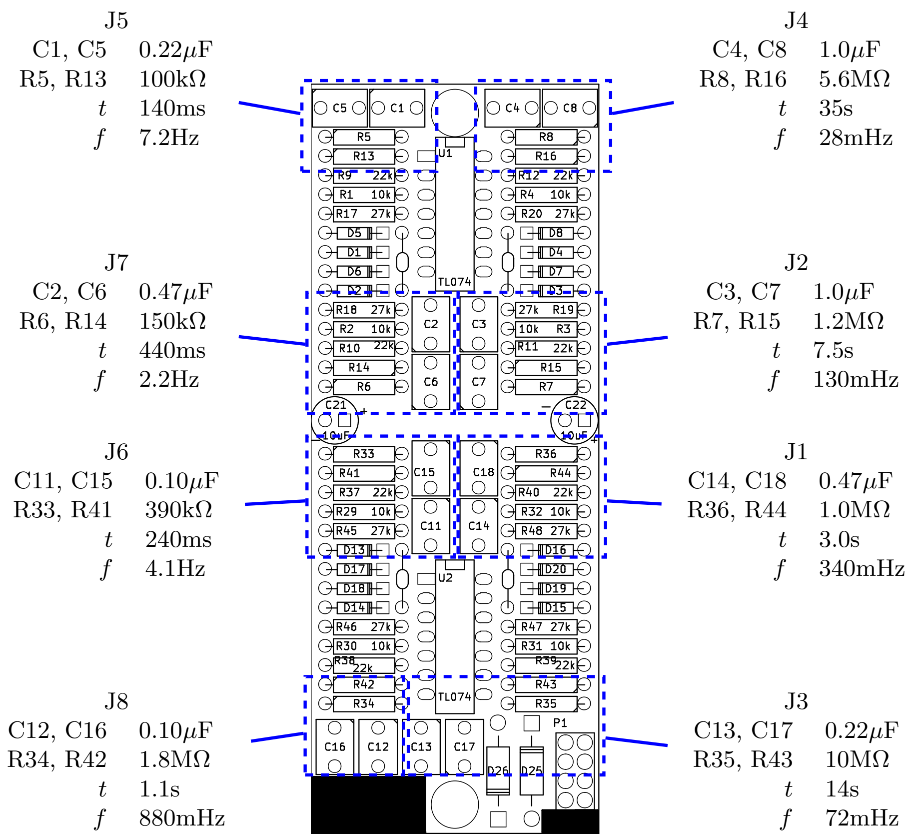
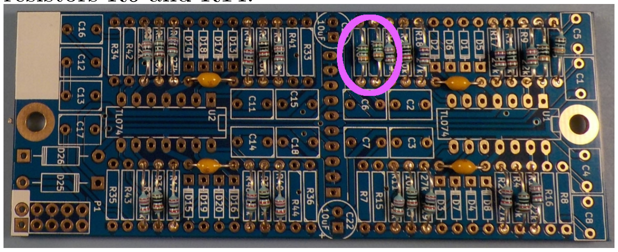
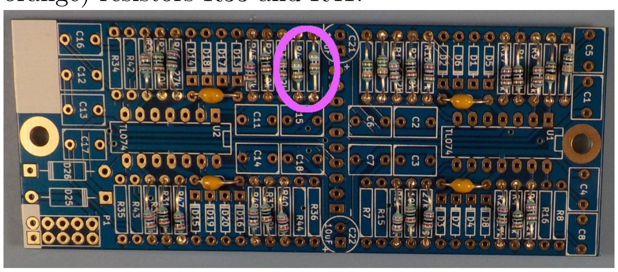


Figure 4: Populating Board 2 for variant C

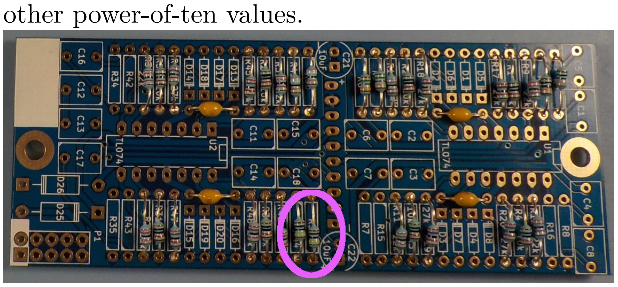
Install the two 150kΩ (brown-green-black-orange) resistors R6 and R14.



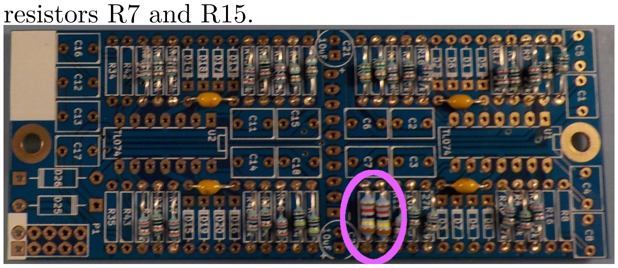
Install the two 390kΩ (orange-white-black-orange) resistors R33 and R41.



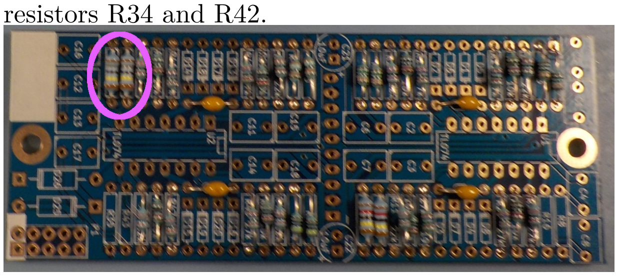
Install the two 1.0MΩ (brown-black-black-yellow) resistors R36 and R44. Do not confuse these with other power-of-ten values.



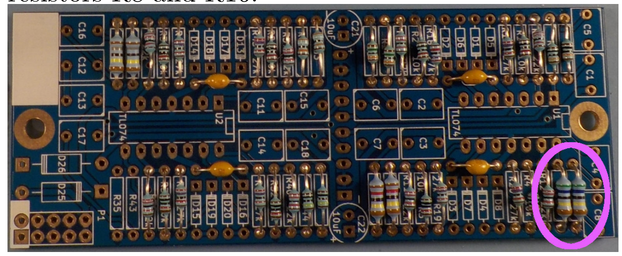
Install the two 1.2MΩ (brown-red-black-yellow) resistors R7 and R15.



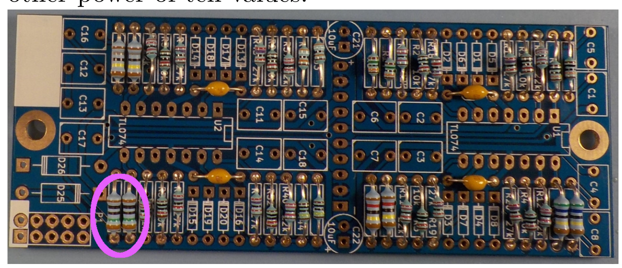
Install the two 1.8MΩ (brown-gray-black-yellow) resistors R34 and R42.



Install the two 5.6MΩ (green-blue-black-yellow) resistors R8 and R16.



Install the two 10MΩ (brown-black-black-green) resistors R35 and R43. Do not confuse these with other power-of-ten values.



Board to board connectors

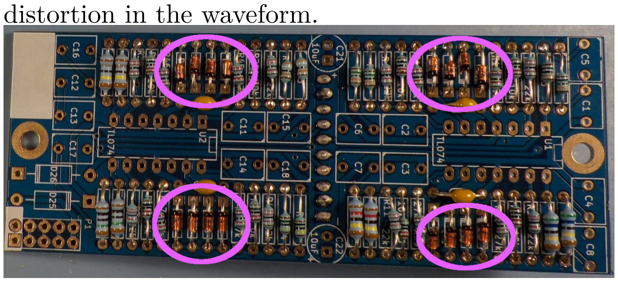
It is important to solder the male header connector that links Board 2 to Board 1 at this time, before adding the film and electrolytic capacitors, because the capacitors surround the solder pads on the front of Board 2 in a way that makes it difficult to work on the connector without damaging the capacitors. For best alignment, you should solder the male connector while it is mated with the female connector on Board 1, and it's convenient to solder the Board 1 connector at this time too.

It is important to solder the connectors to the correct side of each board. Every component has a silkscreen marking on the board and the body of the component should be assembled on the side where the silkscreen is; normally you would then apply solder on the opposite side, where the legs poke through and there is no silkscreen marking. The body of the male connector P6 should be on the side *opposite* the resistors and other components already installed on Board 2. It is the only component on its side of the board. The body of the female connector J9 should be on *the same side* as the places where the resistors are marked for installation on Board 1, and opposite the side where the jack sockets and LEDs are marked for installation. See the photo below and the exploded diagram at the end of this manual.

Assemble the two boards and the two connectors using the M3 machine screws, and 10mm and 11mm standoffs, as shown. The 11mm standoffs should separate the two boards; I suggest using the 10mm standoffs instead of hex nuts for this temporary assembly because they're easier to tighten by hand. Do not confuse the two lengths. Solder the connectors on both boards. Then disassemble them, and set aside the hardware and Board 1 for later.

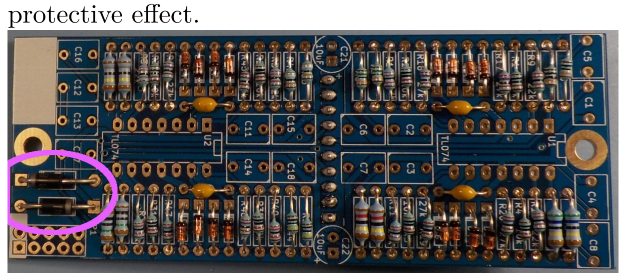
Semiconductors

Install the sixteen 1N5229B 4.3V Zener diodes D1 to D8 and D13 to D20. These control the output level of the oscillators, by gradually bringing the 27kΩ resistors into the circuit as the level increases to back down the gain until it reaches equilibrium. They are polarized components and it is important to install them right way round. Each diode is packaged inside a pink glass bead with a black 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; and the diodes are arranged so that all the cathodes point inward from the edge of the board. Installing one of these diodes backwards will probably result in the output level of the corresponding oscillator being much too low, as well as some asymmetric (second harmonic) distortion in the waveform.



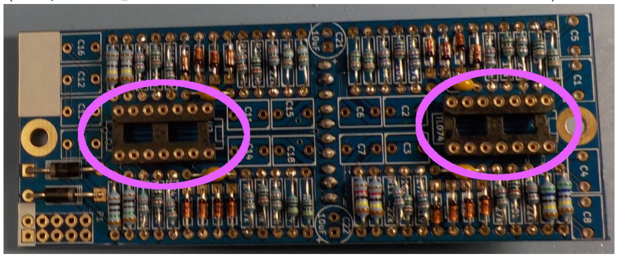
The 1N5229B diodes are the only small glass diodes in an MSK 010 kit, but be warned that if you're doing other electronic construction, then you will probably have many other small glass diodes on hand (for instance, the very popular 1N4148 general-purpose type) and they all look pretty much identical, distinguished only by their electrical properties and near-microscopic code numbers etched onto the glass. Be careful not to mix these diodes up with other types of diodes. Substituting general-purpose switching diodes in this circuit will probably give you output levels that are much too high.

Install the two 1N5818 or SBA130 Schottky rectifier diodes D25 and D26. These are for reverse-voltage protection; they cut off power to the module when the power plug is backwards. They are polarized and it is important to install them in the right direction. As with the Zeners, these diodes will be marked with stripes indicating their cathodes (here, probably white or light grey paint on a black or dark grey plastic package) and those stripes should match the stripes on the PCB silkscreen. The cathode solder pads are also square. Installing these backwards means they will have the opposite of the intended protective effect.



Install the two 14-pin DIP sockets for the TL074 quad op amp chips, U1 and U2. These chips provide amplification to keep the oscillators running. The 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, 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.

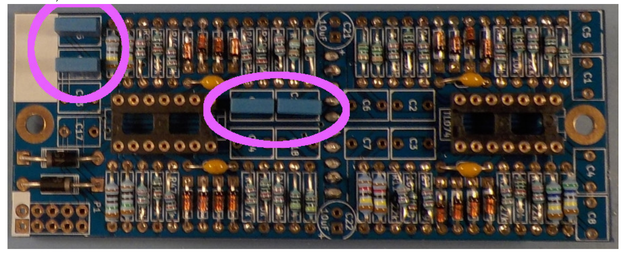
Film capacitors

The film capacitors in this module are used to determine oscillator timing. As with the timing resistors, they are marked on the PCB with their references only, no capacitance values, because they are arranged differently for the different module variants. See Figure 4 for information on which capacitors go where in this variant.

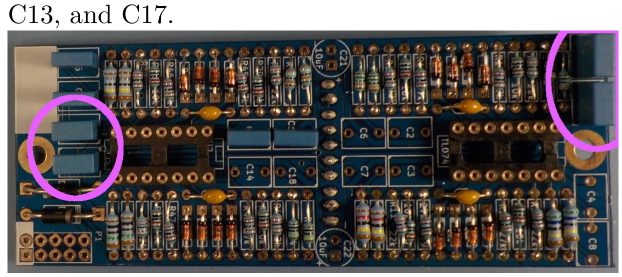
Be careful to identify the values of the capacitors correctly. They may all look very similar. In some cases the physical sizes of the capacitors vary with their value (for instance, 1.0μF will probably be bigger than 0.1μF), but there may also be different values the same physical size. Etched markings on the capacitors will probably use the symbol μ instead of a decimal point, such as μ1 to designate 0.1μF, as opposed to 1μ for 1.0μF. Many digital multimeters will have a "capacitor test" feature which you can use to confirm that you've identified the capacitors correctly. Installing the wrong capacitors in an oscillator will give you the wrong frequency (in case of two capacitors that are the same wrong value) or no oscillation (in case of two capacitors of different values).

Also be careful about the physical aspects of installing the capacitors. I usually stick them in place with vinyl tape before soldering, but it's difficult to get them to stay in at a nice angle. If they're tilted over, that is only really a cosmetic issue; the circuit should work fine as long as both electrical connections are made. These capacitors are also unpolarized, and will work electrically regardless of the direction in which they are installed.

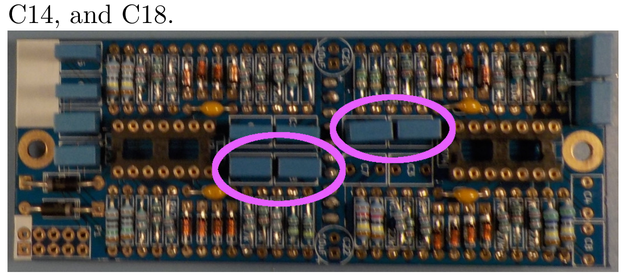
Install the four 0.1μF film capacitors C11, C12, C15, and C16.



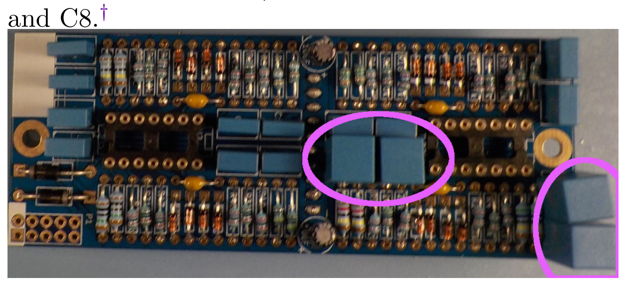
Install the four 0.22μF film capacitors C1, C5, C13, and C17.



Install the four 0.47μF film capacitors C2, C6, C14, and C18.



Install the four 1.0μF film capacitors C3, C4, C7, and C8.[†]

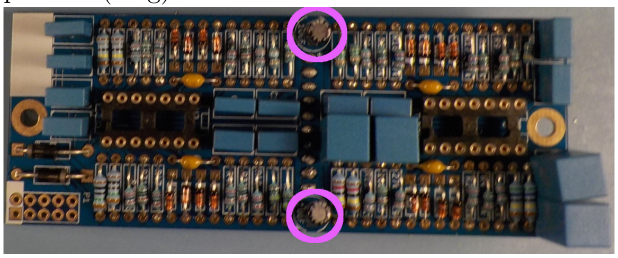


Electrolytic capacitors

Install the two 10μF electrolytic capacitors C21 and C22, 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

[†]This photo shows the 10μF capacitors already installed, but that's really the next step.

with the markings on the PCB: plus and minus symbols in the silkscreen and a square solder pad for the positive (long) lead.

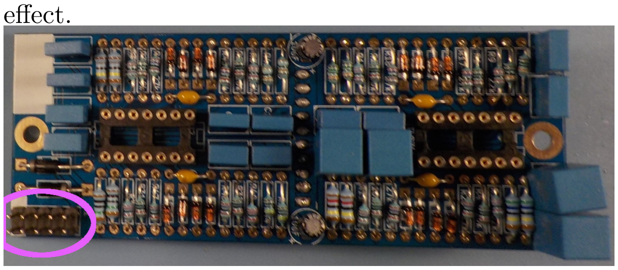


Eurorack power connector

Install the 2×5-pin Eurorack power connector. This connector is not polarized in itself, although the connection it makes is polarized. As with the DIP sockets, you should be careful to get it installed snugly against the board, not tilted at an angle. Use vinyl tape or similar to hold it in place, solder one pin, then check that it is straight before you solder the other pins.

Be aware that both the connector and the copper connections to it on the PCB have relatively large thermal mass. These solder joints will need more heat than usual; and after you have soldered it, the connector will remain hot longer than recently-soldered components usually do. Don't burn yourself.

The six pins in the centre of the connector, that is all except the four corner pins, are for grounding and they are all connected together on the board. Thus, if you accidentally form solder bridges among these six pins while installing the connector, don't waste effort trying to remove them; they will have no electrical effect.



That's all the components for Board 2.

Because some connections on this board operate at multi-megaohm impedances, it may be a good idea to clean the flux residue off of Board 2 even if you are using no-clean flux which would not normally require cleaning. For this type of solder flux, or traditional rosin, use isopropyl alcohol for cleaning. If you used water-soluble solder flux, then cleaning is mandatory and you should use water.

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 in Table 5 for the items needed in this chapter (including the final assembly of the module). It is also assumed you have a finished Board 2 from one of the three preceding chapters, and that you installed J9 on Board 1 while building Board 2.

Fixed resistors

Install the eight 510Ω (green-brown-black-black) resistors: R22, R24, R26, R28, R50, R52, R54, and R56. These are current-limiting resistors for the LEDs.

Install the eight 1kΩ (brown-black-black-brown) resistors: R21, R23, R25, R27, R49, R51, R53, and R55. These are current-limiting resistors for the output jacks, to protect both this module and whatever it's connected to, in case of a short circuit.

LEDs and jack sockets

Follow the procedure for installing the components that go through the front panel carefully; some of these steps will be difficult to perform if done in the wrong order.

First, you should already have installed the 10-pin female connector J9 for joining Board 1 to Board 2. If you have not, install that first according to the instructions in the Board 2 chapter. Be sure the body of J9 is on the side of the board with the silkscreen saying "J9"; the solder joints are made from the other side, where there are no markings. The side with the J9 body, the resistors you just installed, and so on, is called the "front" of the board, and notwithstanding that name it faces *away* from the panel in the finished module.

Install the two 10mm standoffs on the back of the board, where they will connect Board 1 to the panel. Hold them in place by threading on the two 11mm standoffs on the front of the board, where they will separate Board 1 and Board 2. Do not confuse these two lengths of standoffs. The male threads on the 10mm standoffs should go through the holes on Board 2, with the female threads facing the panel to receive the M3 screws, as shown in the photo.

Place (do not solder) the eight jack sockets in the corresponding holes in the back of Board 1. Each will fit in only one way.

Place (do not solder) the eight LEDs (D9 to D12 and D21 to D24) in the corresponding holes in the back of Board 1. Single LEDs are polarized and can be destroyed by reverse voltage. These ones here are special bi-colour devices with two separate LEDs in each package. The internal connection is such that each diode protects the other from reverse volt-

This table is not a substitute for the text instructions.

Qty	Ref	Value/Part No.	
8	D9–D12, D21–D24	L-57EGW	bi-colour LED, Kingbright
2	H4, H8	M3	nut for M3 machine screw
2	H2, H6	M3x10	M3 male-female standoff, 10mm body length
2	H3, H7	M3x11	M3 male-female standoff, 11mm body length
2	H1, H5	M3x6	M3 machine screw, 6mm body length
8	J1–J8	1502 03	switched mono 3.5mm panel jack, Lumberg
8	R22, R24, R26, R28, R50, R52, R54, R56	510Ω	
8	R21, R23, R25, R27, R49, R51, R53, R55	1kΩ	
2	U1, U2	TL074	quad JFET-input op amp

Table 5: Bill of Materials for Board 1 and final assembly.

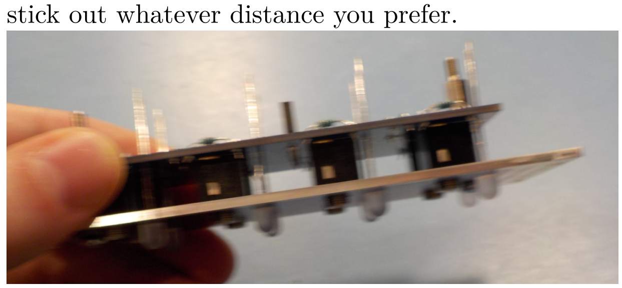
age; so if connected backwards, they will not be destroyed, but the intended green and red colours will be swapped. Each LED lens has one flat side, and one leg shorter than the other on that side. The short leg is Pin 1. Its proper place on the board is marked by a circle with a flattened side matching the direction of the flattened side on the LED lens, and an oval solder pad. The other leg (Pin 2, long, farther from the flat side) goes into the rectangular solder pad. Be sure all eight LEDs are placed right way around according to these clues.

If you want to clean the boards with isopropyl alcohol or a similar solvent, do it before attaching the panel, because the varnish on the panel (at least in the first production run; we may change our panel process in the future) might be damaged by solvents. Also, beware of washing flux or other contaminants into the female connector J9.

Fit the aluminum front panel onto the assembly, with the jack socket bushings going through the corresponding holes, and use the two M3 machine screws to attach the panel to the 10mm standoffs. Use the knurled nuts that came with the jacks, to attach those to the panel. Note that each nut has a smooth side and a side with two notches in it; the notches should go outward, with the smooth side against the panel. Beware of damaging the panel with wrenches, pliers, and similar. If you must use pliers, wrap them with tape to reduce the risk of scratches; but just screwing the nuts on with finger pressure should be sufficient.

Be careful not to attach the panel backwards. The pattern of holes for the standoffs and jack sockets is symmetrical, which makes it possible to fit the panel onto the module with those parts lined up but the LEDs not lined up with their corresponding holes. Make sure all panel parts are able to fit into their holes, before you spend time attaching the screws and knurled nuts.

Turn the assembly over so that the LEDs fall into place. Adjust them by gently pulling or pushing their legs until they all pass through the panel holes and stick out whatever distance you prefer.



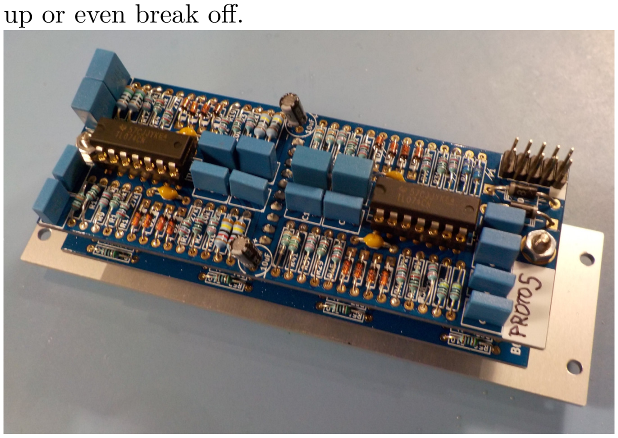
Solder all the jack sockets and LEDs, and snip off the protruding extra length of the LED leads. The jack sockets may require a relatively large amount of solder and heating to fill the corresponding holes, but these joints are structural and should not be neglected. The LEDs, on the other hand, are sensitive to soldering heat and should not be given excessive amounts of solder and heating, though the joints must at least be strong enough not to break if users should accidentally press on the LED lenses. Be careful about soldering near J9; there should be enough room to make these joints, but you must avoid touching the plastic with the soldering iron tip.

Final assembly

It should not be necessary to remove the panel from Board 1 again, nor to unscrew the standoffs. Just add Board 2, carefully fitting its header plug into the header socket 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. Be careful of the capacitors when putting the hex nuts in place, especially at the top of the module where the clearance is tight.

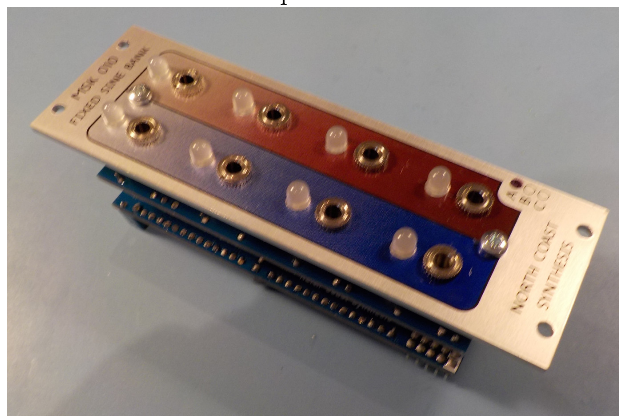
Insert the two TL074 chips in their sockets on Board 2. Be careful to insert them right way round: the end with Pin 1 will be marked by an indentation at one corner or a notch in the end, and this end of the chip should be inserted to match the notch in the socket and on the board silkscreen and the rectangular Pin 1 solder pad. The Pin 1 end of each chip should be at the top when the module is inserted in a rack. A chip installed backwards will probably be destroyed on power-up.

Also be careful that all the legs of each 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.



There is a rectangular white area at the lower left corner of Board 2 reserved for adding a serial number, signature, quality control marking, or similar. Use a fine-tipped permanent marker to write whatever you want there; and, if you haven't done this already, remember to fill in the appropriate circle on the lower right of the front panel to indicate which variant of the module this is. Isopropyl alcohol will probably dissolve marker ink, so do this step after any board-cleaning.

Your module is complete.



Testing

The MSK 010 requires no adjustment or trimming. All the components are fixed-value. It should simply work as soon as it's built. Nonetheless, to guard against mistakes in construction, it's a good idea to do some simple tests before using it in an artistically critical situation.

You will need at least your assembled module, a power supply for it, and a multimeter. An oscilloscope would also be useful for troubleshooting, but is not really necessary.

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 two pins at the bottom, marked with white on the circuit board, are for -12V. The two at the other end are for +12V; and the remaining six pins in the middle are all ground pins. Check between each pairing 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.

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.

Optional: Plug the module into a Eurorack power supply *backwards*, see that nothing bad happens, and congratulate yourself on having assembled the reverse-connection protective circuit properly. Reconnect it right way round before proceeding to the next step.

Blinking lights

Plug the module into a Eurorack power supply and look at the lights on the front. They should all fade from green to red and back, at different speeds, with the slowest one at lower left and the fastest at upper right. The very fastest may change faster than your eye can follow, and appear solid yellow. The very slowest may take over a minute to complete the cycle.

When the module is first plugged in after having been turned off for a few seconds or more, all lights will probably glow *bright* green, brighter than the green that appears in the usual cycle, for a short time as the oscillators start up. This might last up to half a cycle time (about half a minute for the slowest oscillator).

If any of the LEDs fail to light up at all, glow solid red or green (after the startup time) instead of cycling, or cycle at a rate much different from what you expected, then something may be wrong. Disconnect the power and investigate what is wrong.

Oscilloscope test

Power up the module and connect an oscilloscope to each output in turn. Each signal should look like a sine wave, with the frequency and period documented in the relevant "Board 2" chapter ±15%; amplitude 10±2V peak to peak; and little enough harmonic distortion and noise that it looks "clean" on the scope.

Troubleshooting

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.

No response from the module at all; *none* of the lights light up, no signal on the output. Most likely a power problem, such as a power cable plugged in wrong or a short circuit. It might even be a problem in the power supply and not the module itself.

No oscillation in one or more oscillators; a light remains solid red or green for more than a minute, especially if it is brighter than normal. This could be caused by components being switched around; for instance, not the same value for the two time-determining resistors in an oscillator. It also could be caused by bad soldering; check all your solder connections visually. Note that "solid yellow" is normal for the highest-frequency oscillators; that is simply what a very rapid flash between red and green looks like to human eyes.

During prototyping I also observed a problem of this kind that seemed to originate with solder flux contamination washed into the board-to-board connector during cleaning. It appeared that solvent with dissolved flux in it had dried inside the connector and formed a varnish-like insulating film. In one case all the lights went red on power-up and stayed that way; in another, just a couple of oscillators seemed to get stuck. Both were resolved by unscrewing the standoffs and carefully unplugging and plugging back in the board-to-board connector a couple of times. If you see a similar problem in your build, especially if you have solvent-cleaned your boards, it would be worth trying this as a first step before doing anything more drastic.

An oscillator starts, runs for a few cycles, then dies out, with the light going dark. This suggests the loop gain is too low. It is designed with a moderate safety margin, so something has to be wrong for this to happen. Components out of their tolerance range, with values close to the right ones but not as close as the specifications require, is one possibility. Make sure any component substitutions you made were really appropriate. Especially for the lowest-frequency oscillators (which use very high impedance), it's possible that solder-flux residue could also cause this kind of problem. Try cleaning the boards with isopropyl alcohol and a brush. If you used water-soluble flux for your soldering (not recommended), then you should clean with water first to remove any remaining flux, and then isopropyl alcohol to remove the water and any other contaminants.

Four oscillators misbehave, in a checkerboard pattern. That is, the oscillators connected to either J1, J3, J6, and J8; or J2, J4, J5, and J7. Each of these sets of four is driven by one of the two TL074 chips, so if they are all bad in a set, it suggests something wrong with the corresponding TL074. The {J1,J3,J6,J8} set is driven by U2 (on the bottom when the module is mounted vertically) and the {J2,J4,J5,J7} set is driven by U1 (on the top). Check, for the relevant chip, that:

- it really is a TL074, not some other kind of chip;
- 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 at the top and matching the other 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;
- its decoupling capacitors (the small ceramic ones) are installed and there is nothing wrong with their solder joints; and
- if all that turns up nothing, try swapping the two TL074s and see if the set of failing oscillators also changes.

An oscillator's waveform as seen on an oscilloscope has excessive distortion, perhaps appearing more like a square wave or trapezoid, with or without rounded corners, instead of a proper sine. This suggests the loop gain is too high; it's most likely caused by an incorrect resistor value. Also check the amplitude-limiting components (Zener diodes and 27kΩ resistors); if they are not properly connected, the result might be flattened waves combined with a much higher than normal amplitude.

An oscillator's waveform as seen on an oscilloscope contains a significant amount of higher-frequency content, in the kHz or MHz range. This might be just a ripple added to the desired low-frequency sine, or it might be a rail-to-rail square wave overwhelming everything else, at a much higher frequency than the module is intended to produce. Either way, it suggests that the op amp is unstable, which should not be possible in this circuit with the recommended parts. Check all the op amp troubleshooting points mentioned above, and try cleaning to remove solder residue. See if a 0.01μF capacitor connected temporarily in parallel with the op amp's 22kΩ feedback resistor helps, but even if it does, it would be preferable to figure out what's really wrong instead of just soldering that in and hoping for the best.

Regular high-frequency spikes superimposed on the oscillator output, with a repetition rate of twice the power-line frequency (120Hz in North America, 100Hz in many other places): there may be some piece of electrical equipment, such as a lighting dimmer switch, putting interference into your mains grounding system. I observed this while testing an MSK 010 prototype and it took me a while to figure out it was not something wrong with the prototype. Make sure your oscilloscope is plugged into the same mains power circuit as your bench power supply, and try turning off any dimmer switches.

The module seems to work for a while, but then suddenly fails with at least four LEDs going solid-colour or dark; it works again when you turn the power off and on again. This suggests either or both of the chips have gone into "latch-up," which could be triggered by spikes on the power supply, static electricity, or bad voltages applied to the output jacks; but also check the solder joints for any that may be loose.

Apparent crosstalk between oscillators: do not trust the LEDs as a way of detecting this. The LEDs are driven by simple resistors from voltage sources; that means when the output voltage of a slow oscillator is close to the LED's minimum forward voltage for turning on, even the tiniest variation in voltage will push it back and forth across the boundary, resulting in a disproportionate fluctuation in light output. Combining that effect with optical illusions and the power of suggestion, it is easy to think that you *see* the slow oscillator LEDs wavering in time with the relatively fast ones, when you would not be able to *hear* it. The tiny amount of visible wavering or instability I've observed in my prototypes is best thought of as just part of the charm of analog, and not a problem. However, a really large amount of crosstalk verifiable by objective measurement of the output waveforms may indicate issues with the ground connection from the module to the power supply.

Patch Suggestions

Use the MSK 010 as a modulation source for a classical analog oscillator; here, it controls exponential FM and pulse width.

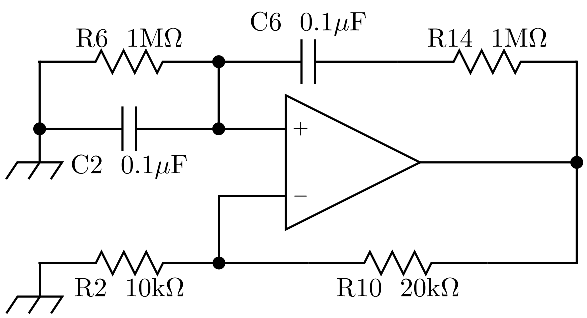
For modules that don't have built-in attenuators, it can be useful to run the outputs through an external attenuator like the Triatt. The Clouds is a good candidate for modulation with the MSK 010 because it has many different control voltage inputs; you might even want more than one MSK 010 to take full advantage of it.

A small amount of sine modulation on a BBD's clock gives a sound much like an unstable tape recording.

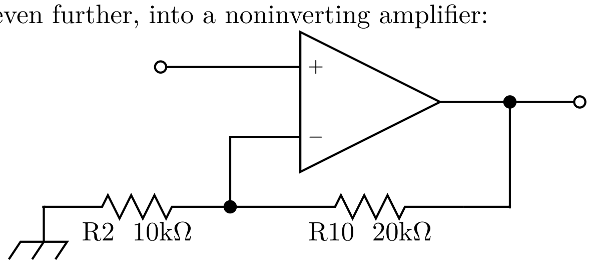
Mix slow sine waves and run them through a quantizer for an automatically-generated but non-random melody.

Circuit explanation

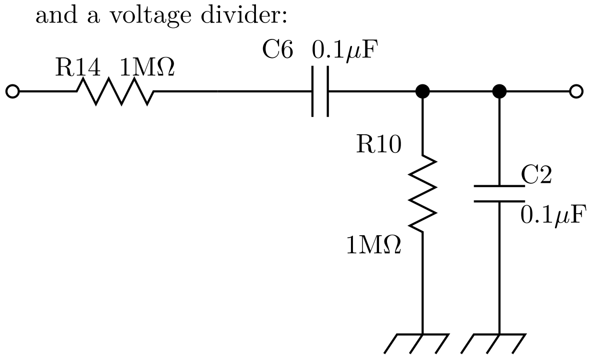
The MSK 010 contains eight basically identical oscillators, differing only in the resistor and capacitor values that determine their frequencies. The complete circuit for one of them is shown in Figure 5, but to better understand the circuit, let's look at a simplified version first. Some of the component values have been changed (or filled in, where they're unspecified on the main schematic) for a more understandable presentation.



This is the core of a "Wien bridge oscillator," named for an impedance-measuring circuit invented by Max Wien in 1891, which its feedback network superficially resembles. We can actually break it down even further, into a noninverting amplifier:



and a voltage divider:



Think about the voltage divider first. At very low frequencies, capacitors look like open circuits, with high impedance, infinite at zero frequency (DC). So for DC, the divider has infinite impedance on the top (1MΩ in series with infinity) and 1MΩ impedance on the bottom (1MΩ in parallel with infinity). That gives zero output; no signal from the input gets through.

At very high frequencies, capacitors have low impedance, going to a limit of zero at infinite frequency. So if we imagine feeding an infinite-frequency signal into the voltage divider, it has 1MΩ impedance on the top (1MΩ in series with zero) and zero impedance on the bottom (1MΩ in parallel with zero). Again, no signal gets through.

For frequencies that are neither zero nor infinite, the capacitors have impedances that are also neither zero nor infinite, and then the voltage divider lets through some amount of signal. So now we have a rough description of the behaviour of this circuit: for high and low frequencies, it blocks the signal, and for frequencies in between, it lets some signal through. It's a two-pole passive band-pass filter.

It is reasonably simple to show using calculus, though I will omit the details here, there there must be some specific frequency in between zero and infinity at which the output is maximized; and that frequency happens to be the one where the capacitive reactance of the two capacitors is equal to the resistance of the two resistors. This is the centre frequency of the band-pass filter. Where R is the value of each resistor and C the value of each capacitor, the centre frequency f is given by

$$f = \frac{1}{2\pi RC} \,.$$

With the example values of 1MΩ and 0.1μF, this works out to 1.59Hz.

Now, how much signal actually does get through at the centre frequency? At 1.59Hz, a 0.1μF capacitor has a capacitive reactance of 1MΩ. But capacitive reactance is not the same as resistance; the two are actually at right angles to each other on the complex

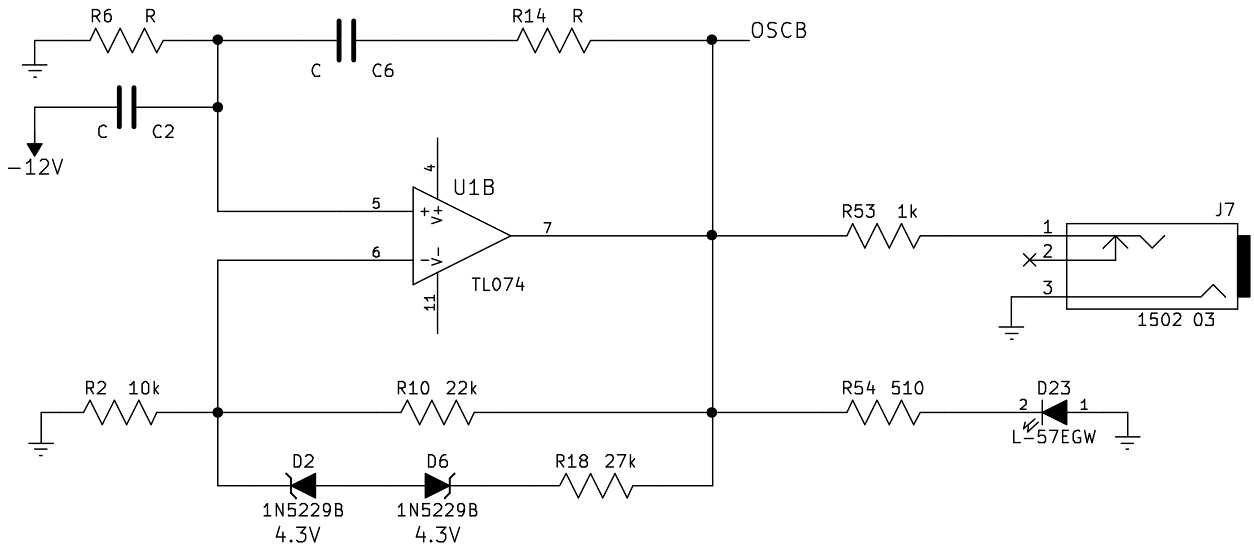


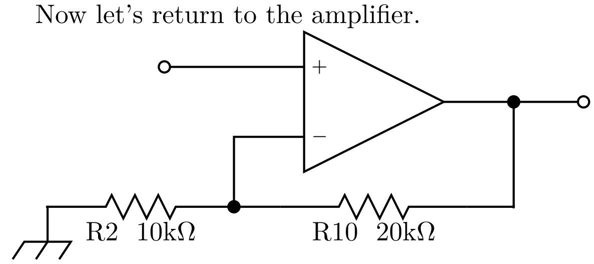
Figure 5: One oscillator.

plane. Without going into a lot of detail on that, we can get an intuitive understanding by saying that at the centre frequency, the top of the voltage divider contains two 1MΩ impedances at right angles to each other, in series. Series impedances add as vectors, and adding two equal-length vectors at right angles to each other gives a new one $\sqrt{2} = 1.414\ldots$ the length of the inputs. (Pythagorean Theorem, 45-45-90 triangle.) So the top of the voltage divider is an impedance with magnitude 1.414MΩ.

On the bottom, we have two 1MΩ impedances at right angles to each other in the complex plane, connected in parallel. For parallel components, the admittances (reciprocals of impedance) add as vectors. So each of these components has an admittance of 1μS (microsiemens, the inverse of megaohms), and those add as right-angled vectors for an overall admittance of 1.414μS for the pair of them, equivalent to an impedance with magnitude 0.707MΩ.

Just looking at the magnitudes of the top and bottom impedances in the voltage divider, it looks like a 2:1 ratio, 1.414MΩ on top and 0.707MΩ on the bottom. Then we can imagine that 1/3 of the voltage on the input might appear at the output. This intuitive argument isn't mathematically correct because it neglects the phases of the signals. To get a really correct result, we should calculate with complex numbers all the way through, but if we do that, it turns out the intuitive estimate was right after all: at the centre frequency, the voltage on the output really is 1/3 (as a pure real number, no phase shift) times the input voltage.

Now let's return to the amplifier.



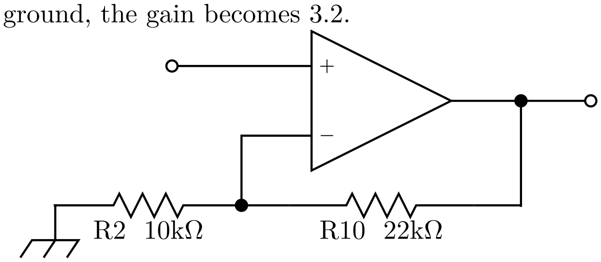
This is a standard noninverting amplifier circuit built with an op amp. The input voltage is applied to the positive input of the op amp, and the op amp will drive its output to whatever voltage is needed to make the negative input match the positive input. The negative input happens to be driven by a voltage divider to 1/3 of the output voltage; so the output voltage has to be three times the input voltage, as long as the op amp is able to sustain that.

The oscillator circuit combines this amplifier, with voltage gain 3, with the resistor-capacitor band-pass voltage divider, which has voltage gain 1/3 at the centre frequency, and less at all other frequencies. If there happens to somehow already be a sine wave at the centre frequency on the op amp output, then the band-pass voltage divider cuts its voltage by a factor of three, and the amplifier boosts it back up to the original voltage. So the overall circuit can sustain oscillation at that frequency. And *only* at that one frequency—because signals at any other frequency will be attenuated more in the band-pass filter, then amplified with gain only 3 in the amplifier, and so they come back at a reduced voltage each time through the loop and die out completely after a few cycles.

But there are still a few problems. How does the oscillation get started? If there is no signal at all, this circuit seems like it won't create one. How can we predict the amplitude of the signal? And what about non-ideal components?

If we are using real-life components, a 1MΩ resistor might be specified as 1% tolerance, and its actual value could be anywhere from 0.99MΩ to 1.01MΩ. If we are unlucky enough to get the resistor (and, worse, the capacitor) on the top of the voltage divider a little larger than its target, and also the components on the bottom a little smaller, than the output of the voltage divider could be somewhat less than 1/3 the input voltage even at the frequency where the output voltage is maximized. And then if the amplifier really has gain of exactly 3 or less (less is quite possible because of tolerances in its own resistors), the signal will come back a little weaker every time it goes around the loop, and eventually die out.

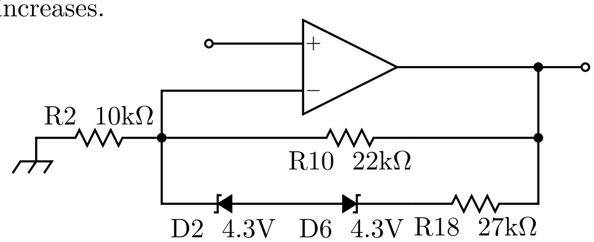
So, we might make the gain of the amplifier a little more than 3 to compensate for any extra losses that might exist in the rest of the circuit. With a 22kΩ feedback resistor matched against the 10kΩ to ground, the gain becomes 3.2.



Now as long as the output of the voltage divider is more than about 0.31 times the voltage divider's input, the amplifier will boost it above its original level. Any oscillation at the centre frequency will grow bigger and bigger, without any obvious limit.

The op amp cannot produce an unlimited output voltage, so something has to give. What happens is that once the amplifier drives its output to the maximum voltage it can handle (which would be about ±9V with the components and power supply used in the MSK 010), it stops acting as a linear amplifier and starts producing distortion. On an oscilloscope, it looks like the tops and bottoms of the sine waves are getting clipped off, leaving a roughly trapezoidal waveform. In spectral terms, what is happening is that some of the power is being diverted from the sine wave into harmonic frequencies. The harmonics will not make it through the band-pass filter in any significant amounts, so they will not be re-amplified as parasitic oscillations, but they get re-created on each pass from the leftover power that cannot go into raising the voltage any further.

So, what can we do about this? If the gain is too low, the oscillations will die. If the gain is too high, the op amp will be driven into clipping and create a lot of distortion (as well as simply an output voltage higher than we want). And controlling the gain extremely precisely with high-precision components and trimmers or similar, is expensive. The solution is to automatically reduce the gain a little as the voltage increases.



At low output amplitudes, the output voltage stays near zero, and there is never enough voltage across the back-to-back Zener diodes for them to conduct. That entire branch of the circuit has no effect, and the gain is 3.2.

At higher voltages, and in particular, once the output voltage goes past 8.6V peak to peak, the diodes will start to conduct. Then current can flow through them and R18 in addition to R10, reducing the effective resistance in the feedback loop and therefore the gain. At the extreme, for very high output voltages the voltage drop across the diodes (maximum about 4.9V total, for one reverse biased as 4.3V and the other forward biased at 0.6V) will be negligible, and the feedback resistance will approach that of the parallel combination of R10 and R18, namely about 12.1kΩ. That would give a gain of 2.2 through the amplifier.

The output voltage never really goes that high, though. What really happens is that with very small signals, the gain is 3.2, causing the amplitude to increase. Once it gets to about 10V peak to peak, the increasing current through the diodes cuts in R18 enough to reduce the gain to 3.0, and the signal stabilizes at that amplitude. If component imperfections, or changes in value caused by temperature and aging, cause it to require a little more or less gain, then the amplitude will increase or decrease a little until the gain hits the right level for the oscillation to just sustain itself. Much the same thing happens in response to imperfections in the amplifier circuit itself.

There is a price to be paid for this automatic adjustment: the gain is changing throughout the oscillation cycle (3.2 near zero crossings, 3.0 or slightly less at the peaks) and that means the amplifier is no longer operating linearly. Nonlinear amplifiers couple some of their output power into harmonics. As a result, there will be a bit of distortion in the output. In the MSK 010, especially given the intended application as a modulation source, this distortion is small enough not to worry about. But if we wanted a *really* pure sine wave, we would need an even cleverer way of controlling the gain, with corrections applied throughout the cycle over a longer period.

There is a tradition of using incandescent light bulbs for gain control in Wien bridge audio oscillators, to the point that some people incorrectly think the use of such is what makes it a Wien bridge oscillator. The light bulb would go in place of R2. As output amplitude increases, the filament heats up, which causes its resistance to increase, and therefore the gain decreases. It maintains a stable output level in the same way that the MSK 010's Zeners do. The time taken for the light bulb to heat up and cool down is much longer than an oscillator cycle, so the gain is not changing much during the cycle, and the distortion is very low. Hewlett-Packard's first product was a sine oscillator with this type of gain control.

Unfortunately, it's hard to get the right kind of incandescent light bulbs anymore, they aren't compatible with modern electronic manufacturing processes, and they wouldn't work in an LFO like the MSK 010 anyway because the thermal time constant of the light bulb (a fraction of a second) needs to be much longer than the oscillator cycle time (up to a minute in our case). But it remains a good trick to know about for the cases where it's applicable.

Looking at Figure 5, a few more refinements are apparent. For one thing, the capacitor in the bandpass filter is connected to the negative power supply instead of to ground. That is to help with startup; without it, the oscillator would just be amplifying its own thermal noise until that got to be enough to sustain oscillation, and that kind of start-up takes longer than is desirable. It's observable in practice with the MSK 010 circuit on a breadboard, or with an "oscillating filter" type of LFO such as an Intellijel Dr. Octature II: at initial power-up in LFO mode, there's a delay, minutes long at the slowest setting, before the lights light up.

Connecting the capacitor to -12V instead of ground means that at power-up time, the oscillator will be much closer to its stable oscillating state. The capacitor is normally fully discharged at power-up. Applying power pulls the op amp negative input almost to the negative power rail, forcing the output high and the amplitude-limiting Zener diodes to conduct at their maximum. Within a fraction of a cycle time, they have it on track at the normal amplitude level.

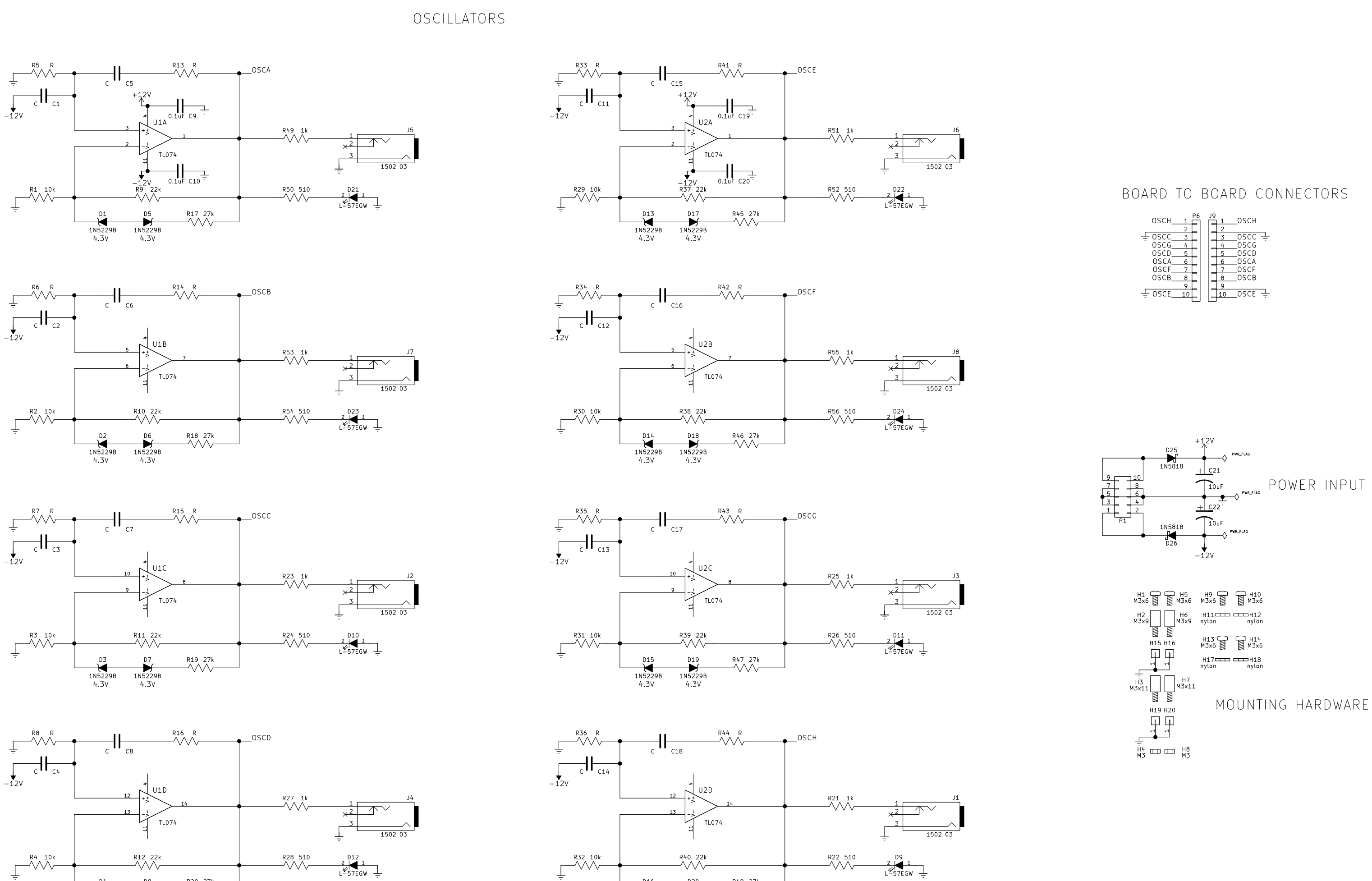
One consequence of this design is that the -12V power supply needs to be clean, because noise there can be coupled into the oscillator output—but clean negative power is a general requirement of op amp circuits anyway, and so is something we can hope for in a synth environment. Another consequence is that there will be a static DC charge of 12V on the capacitor. That means it's important to use a plastic film capacitor here and not a ferroelectric ceramic type, which would suffer capacitance degradation given a DC voltage like that. But the need for close tolerance on this timing capacitor pretty much already meant that we had to specify it as plastic film anyway.

Also visible in the full schematic are the current-limiting resistor R53, which prevents damage to other modules and disruption of the MSK 010's cycle should the output get shorted out or patched into another output; and the bi-colour LED D23 with its own current-limiting resistor R54.

Engineering 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 mechanical drawing of the front panel showing the locations and sizes of the holes in it; and
- an exploded isometric drawing showing how the boards and hardware fit together.



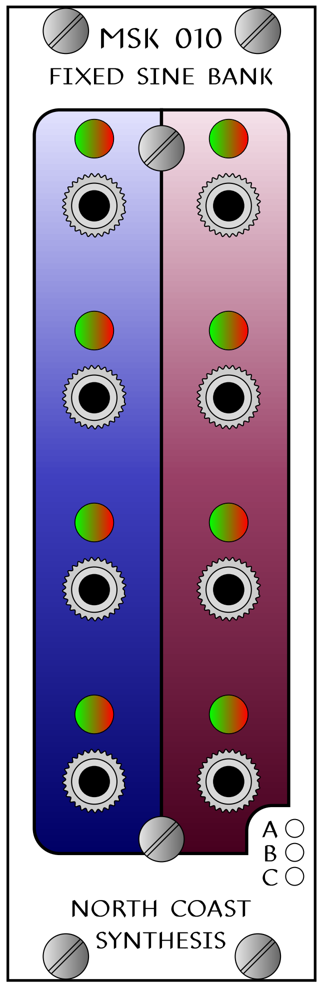
LEDs are Kingbright L−57EGW bi−colour, rated for up to 20mA in either direction to produce 30mcd GREEN light (when forward biased according to the circuit symbol) at 2.2V drop, or 14mcd RED (when reverse biased) at 2.0V drop. Current−limiting resistors are 510ohm, calculated to respect the current limit even if the op amp output goes to +−12V; at nominal output of +−5.5V, this gives 6.8mA estimated 4.8mcd RED, 6.5mA estimated 9.7mcd GREEN.

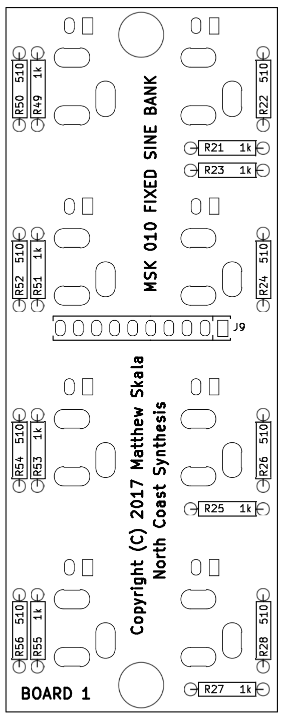
Each oscillator's frequency is determined by two resistors (same value) and two capacitors (same value), shown as values "R" and "C" on the schematic. Frequency is given by the usual formula for RC frequency:

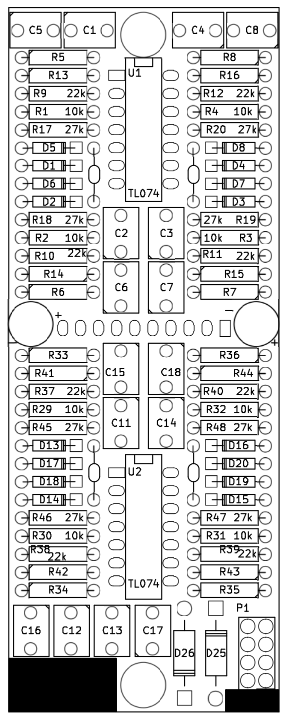
$$f = \frac{1}{2\pi RC}$$

MSK 010 Fixed sine bank

$Id: manysine.sch 8238 2020−10−07 19:32:01Z mskala $ | 1/1


MSK 010
FIXED SINE BANK
A
B
C
NORTH COAST
SYNTHESIS

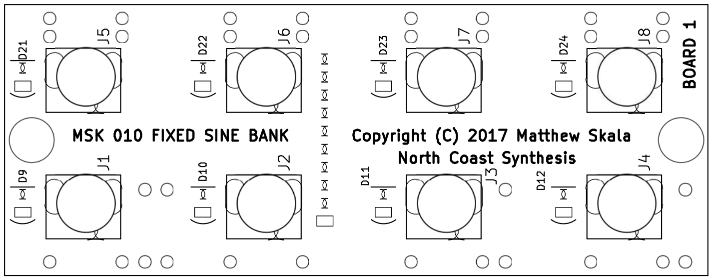


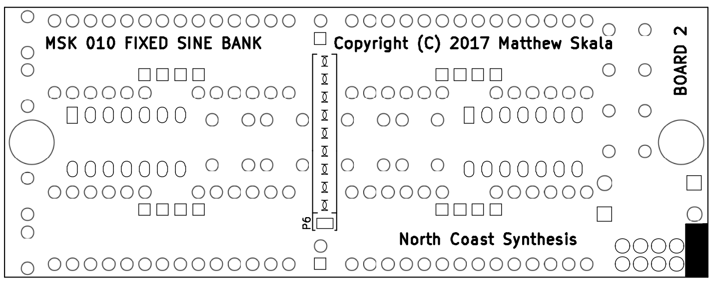


MSK 010 Fixed Sine Bank

$Id: manysine.kicad_pcb 5468 2017-04-19 19:16:49Z mskala $

1/3

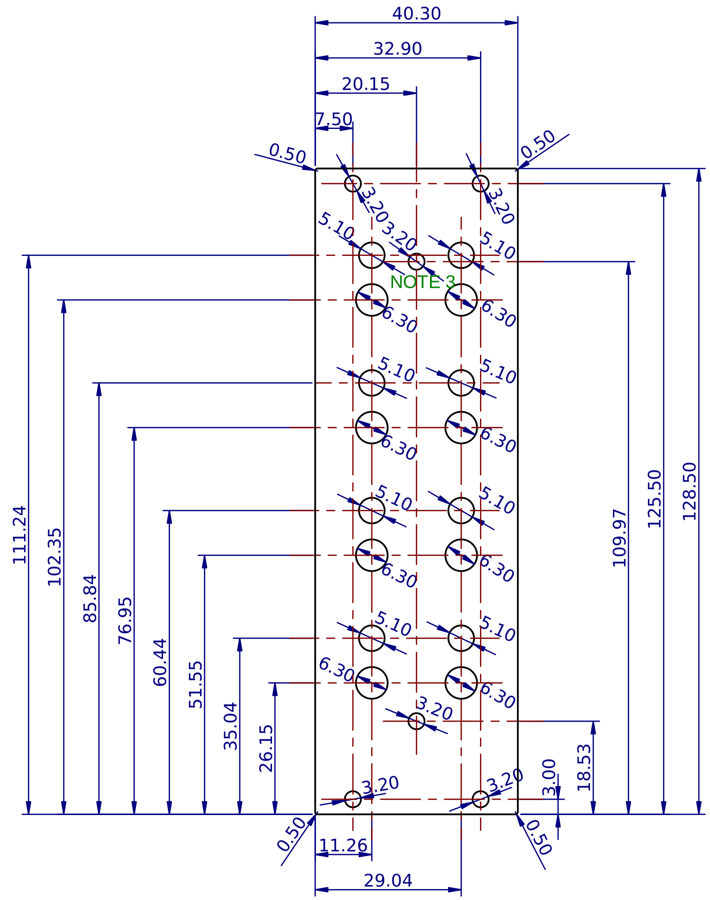




MSK 010 Fixed Sine Bank

$Id: manysine.kicad_pcb 5468 2017-04-19 19:16:49Z mskala $

1/3



NOTES

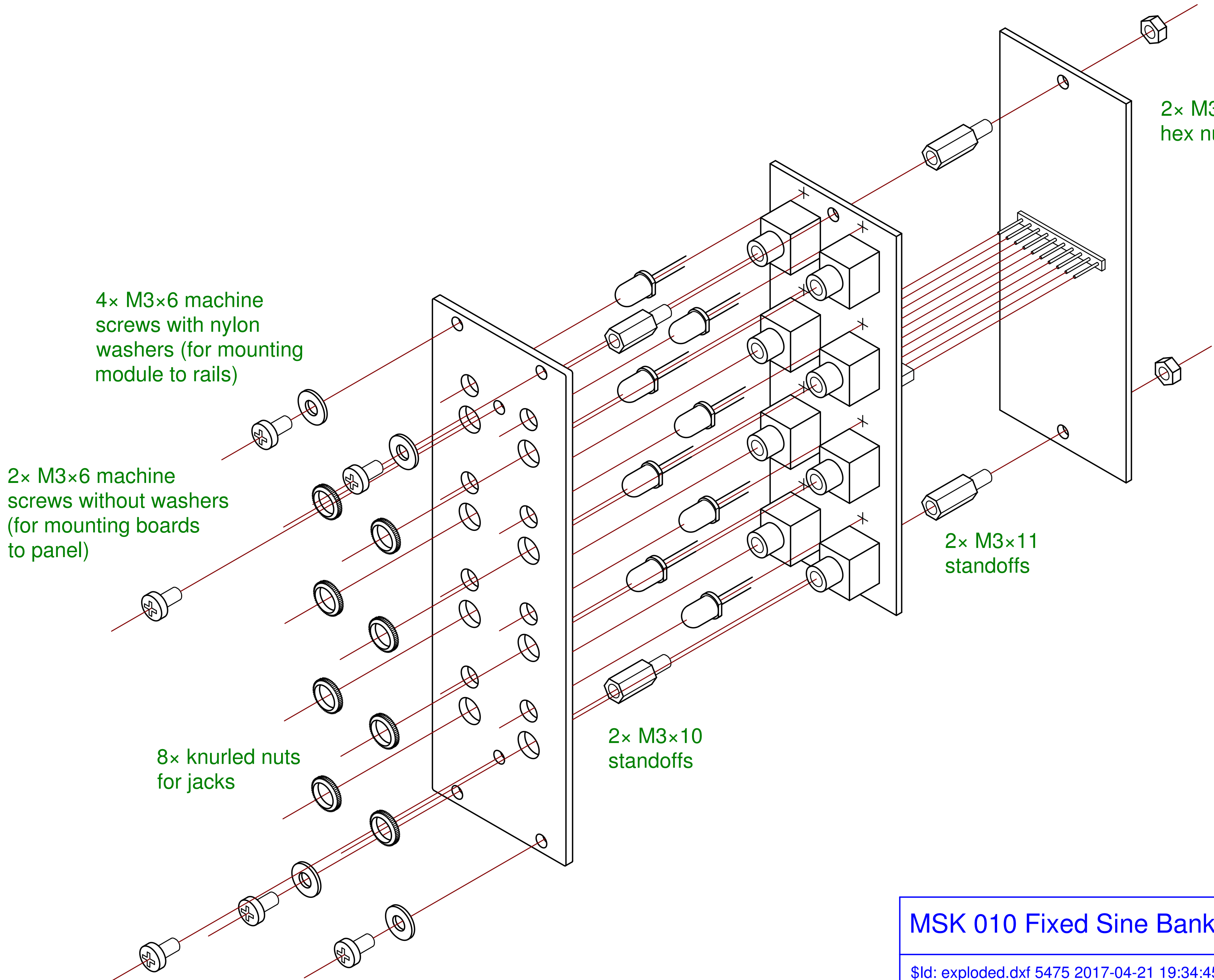
1: All dimensions are millimetres with tolerance +/- 0.10mm.
Do not scale off drawing.

2: Material is aluminum, 2.00mm thick. Overall dimensions are 128.50mm by 40.30mm, per Doepfer spec for an 8HP Eurorack synthesizer module.

3: Do not confuse similar vertical positions. The 3.20mm hole is centred 109.97mm from the bottom edge. The 5.10mm holes are centred 111.24mm from the bottom edge.

MSK 010 Fixed Sine Bank panel mechanical

$Id: panel-mechanical.dxf 5275 2016-12-18 00:10:17Z mskala $ | 1/1



MSK 010 Fixed Sine Bank exploded

$Id: exploded.dxf 5475 2017-04-21 19:34:45Z mskala $

1/1