# Octal 16-Bit DAC

Todd P. Meyrath[1]
Florian Schreck

*Atom Optics Laboratory*
*Center for Nonlinear Dynamics*
*University of Texas at Austin*


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See disclaimer[2]

Here, we present the design of an octal 16-bit DAC based on the DAC7744 from Texas Instruments. The device here is general purpose and may be easily controlled by a variety of systems involving a simple parallel bus. The basic features are as follows:

**Eight channels per board**:

- 8-Bit parallel input address bus (plus one strobe bit, 9 total)
- 3 lowest bits select DAC on board (see output table below), the other 5 bits are board select with local address set by DIP switches. The strobe bit also has a DIP switch so it may be set as a high or a low strobe as desired.
- typical digital clock frequency may be 100 kHz to 1 MHz (we use 500 kHz) for 24 input bits (plus one time narrowed strobe bit), 12 to 24 Mbps.

**Each Channel**:

- 16-Bit accuracy
- ±10V scale, reference drift 3ppm/C, easy to change to ±5V by using different values of the LT1019 reference series.
- Buffered BNC outputs for 50 Ω loads, 250 mA max per channel

**Advantages and Disadvantages**:

The circuit is relatively simple to understand from the schematic and is competitive with professional output boards such as those produced by National Instruments.

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[1]Please send comments, questions, corrections, insults to *meyrath@physics.utexas.edu*

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A principle disadvantage of this design is cross talk. As opposed to a design with 8 totally independent DACs and voltage references, this design uses the DAC7744 quad DAC sharing voltage references among the four outputs. This may produce cross talk of order the least significant bit between the four channels when sweeping. The circuit has several advantages: firstly, it is inexpensive in comparison to National Instruments boards (order $1500). This circuit costs about $200 ($50 per PCB when buying 10, $45 per DAC IC (2), plus output buffers, opamps, capacitors, logic circuits) and the fun of building it yourself! A second advantage is the control bus, this setup allows one to set up a data and address bus system however one wants (digital output board, parallel port, USB to parallel, etc). The addressing and data writing is very simple with a 16-bit parallel data bus and an 8-bit parallel address bus. This means that the computer may control many such boards or other types using a similar bus setup. The digital lines may also extend far from the computer along a single 50 conductor ribbon cable. This may allow one to keep the precision analog outputs short. Our system using 8 address bits may have as many as 256 16-bit analog outputs (unless addresses are used for other devices as well). Naturally only one 16-bit output may be addressed on a single digital cycle, however, for the cold atom experiments that we run this is hardly a limitation. We run our digital bus at 500 kHz. The circuit is in convenient form for laboratory electronics with BNC outputs which are buffered to drive the common 50 Ω loads. The board may be easily panel mounted in an enclosure using the BNC receptacles. Such output stages are not available straight from the various (National Instruments) PCI boards and therefore must be externally added (at great expense) – which requires a similar amount of labor to construct as these designs. The generality of the bus system to run these boards is a major advantage in terms of extendibility. Where as, PCI (or PXI) type analog boards have the major constraint of limited PCI slots.

One can also consider this design in comparison to the old-fashioned method of saving money – using potentiometers. Here, we have about $25 for a fully flexible stable analog output. Most potentiometers cost from $10 to $15 and a precision locking knob can cost a similar amount, plus the minor expenses of voltage references, potentiometer designs are not much cheaper, if at all.

The limit on the speed here is the settling time of the DAC which is specified to be 0.003% in 10 $\mu$s Giving a not-as-settled output for our clock rate. In principle, if this is tolerable, the update time can be sub-$\mu$s. There is also a limitation introduced by the lack of impedance matching on the board's digital inputs, however this should not be a problem until far beyond reasonable update times for these DACs. Should the bus system be run at a much higher frequency in any case, an impedance matched buffer board may become necessary near the digital inputs to the DAC board.

**Outputs**:

Output BNCs are labeled J1 to J8 left to right on the front panel. Their addresses are given in the following table, where X's are setable for board select. Address bits are referred to as bits 0 to 7 and bit 8 is strobe.

| Board Version 2 | | |
|---|---|---|
| Address | Output Conn. | Label |
| XXXXX 111 | J1 | Out 7 |
| XXXXX 110 | J2 | Out 6 |
| XXXXX 101 | J3 | Out 5 |
| XXXXX 100 | J4 | Out 4 |
| XXXXX 011 | J5 | Out 3 |
| XXXXX 010 | J6 | Out 2 |
| XXXXX 001 | J7 | Out 1 |
| XXXXX 000 | J8 | Out 0 |
| The value of the label is the amount to add to the base address XXXXX000. | | |

**Comments on Construction**:

Surface soldering is not as hard as it looks! We give two methods here, the first is what we used first which is to solder pins one-by-one. The second is using solder paste, see below under the 'easier soldering method'. Soldering items to the surface is easy with a standard iron with a small tip (we used a 0.01" tip). The trick is removing them if necessary – you have to obtain special tips or simply cut them away, *i.e.* with a high speed rotary tool. A few tips for soldering:

- The pads already have a solder mask. Put liquid solder flux on the pads before soldering.

- Use a small set of tweezers and dental tools to position the items. A thin piece of tape may be useful for holding the ICs down for the initial solder connections.

- For SOICs and 1206 chips (resistors and capacitors) it is easy to simply solder one pin while gently pressing the item downwards to keep it from moving. Once one half of the 1206 or a few pins of the SOIC are attached, it is easy to solder the others. The trick is holding the item steady while attaching it in the first place, but this may be done with tape.

- Very small pins, such as the SSOP package (the DAC), require special attention. A procedure for soldering the DAC is shown in Figure 1 and is as follows: (a) A clean new board has a solder mask, the solder mask does not have enough solder to attach the pins reliably to the board. (b) Apply liquid solder flux to the pins. (c) Add solder to each pin, this can be done by smearing solder from the iron across the pins and then striking them with the iron tip in the long direction. It should leave a semi-sausage on each pin. This additional solder is critical to making a reliable contact. (d) Apply more solder flux. (e) Place the chip on the pad and attach with masking tape. The IC will not lay perfectly flat, but close if the additional solder is sufficiently uniform, it is not totally important. (f) Heat pins in sets with a clean iron. This causes the solder to flow and stick to the pins. It may be useful to press the IC with a finger as well. (g) Remove tape, the IC is now attached to the board. (h) Apply more solder flux. (i) Heat pairs of pins and pads adding a small amount of solder each time. Keep the iron hot so that a small amount of solder will go to the iron tip. Be sure to hold long enough to allow the solder to reflow at the pin. Do not add too much solder at risk of attaching neighboring pins together. (j) Finished soldering, each pin should have a shiny solder bead. (k) Clean off solder flux with isopropanol or flux remover. For this procedure, we used a 0.01" soldering iron tip. The addition of the solder to the pad is very important, without it, there is little attachment of the bottom of the pads and it is also difficult for solder to flow onto the connection.

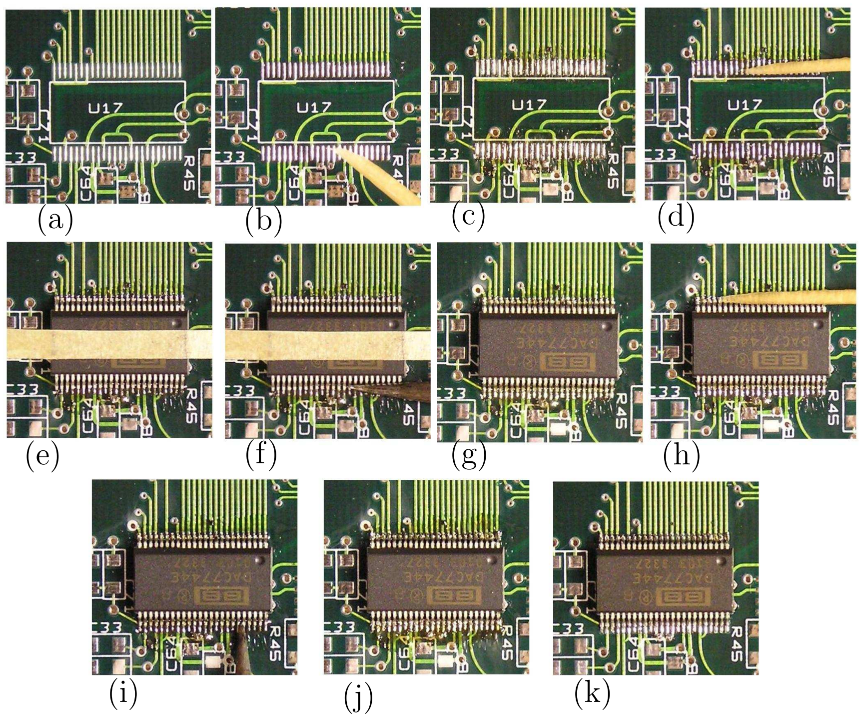



Figure 1: Soldering the DAC, see text for explaination.

It is suggested to solder items on in the following order:

- The DAC chips: these are the hardest and may require soldering iron acrobatics that would be hindered by large components (connectors, capacitors, etc). After the soldering of these ICs, each pin connection should be checked and it should also be verified that there are no solder bridges between pins. It is very important that these connections are all solid, to test this, one may give the board a small amount of torsion while it still has only the 2 DAC ICs. Any bad connections should reveal themselves at this point.

- The SOIC ICs: these are not very difficult, but it is also convenient to not have obstacles.

- The passives: the 1206 components are easy. This completes the surface mount devices.

- The through-hole devices: the connectors, large capacitors, DIP switches, BUF634 ICs. Every kindergartner knows how to solder these.

**Easier Soldering Method**: We used solder paste (Kester water based solder paste, KE1512-ND from Digikey electronics). The solder paste is applied to the pins. For the solder reflow, we used a standard toaster oven and brought the temperature to about 220°C. Note: the DAC is a moisture sensitive device, so we first baked it out at about 120°C for several hours. See the website:
`http://www.seattlerobotics.org/encoder/200006/oven_art.htm`
for amateur solder paste ideas.

**Comments on buffer heat sinking**:

It is absolutely necessary that the BUF ICs each have a small heat sink attached to them, even if you expect that it will drive very little current. Un-sinked buffers will over heat in time. These buffers have an internal thermal shut off which means that they will not burn up all by themselves. However, the thermal shut off can cause major errors in output signals. The errors will not manifest themselves as a zero output single but rather large signal spikes and dips as the buffer turns itself off when it gets too hot and then back on again periodically which may typically be on the ms timescale. The simple moral to the story: heat sink the buffers, and use a small fan.

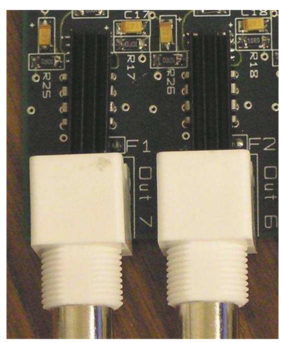



Figure 2: Heat Sinks. These small heat sinks were simply attached to the top of the BUF ICs with 5 minute epoxy.

**The Printed Circuit Board**:

The PCB is a four layer board with signal lines on the top and the bottom. The second to the top layer is the location of the two ground planes (one analog and one digital) and the third from the top is the three power planes (+5 V and ±15 V). All ICs are located on the top as well as most passives. There are also various small items on the bottom. The PCB was designed using the free software from PCB123, this company produced our circuit boards. For the design presented here, the PCB cost was $512 for 10 boards including silk layer charges. The software and information is

available at the web site *www.pcb123.com*. The design of the board is shown in the printout pages near the end of this document and the design file is available at the web site
`george.ph.utexas.edu/~control`

**Circuit Theory**:

The DAC concept is explained on the DAC7744 data sheet available from Texas Instruments and there is no need to discuss it here. Here we discuss the basic idea of the digital and analog circuits on the board.

*Digital Circuit*:

The input to the digital side consists of a 50 pin input header for a 50 conductor ribbon cable. The signals are spaced with ground lines between them giving 25 digital signals. The first 16 are the data bit lines, the next 8 are the address bus lines (as discussed above), and the final line is the strobe bit. The logic circuit works as follows. The strobe signal enters the comparator and is sent out if the local address matches. The logic gates after the comparator insure that only one of the DACs receives the chip select (CS) signal to load the new data bits into its memory latch. Address bit 2 chooses the DAC IC and bits 0 and 1 choose the channel on that DAC. After the new data is loaded, the "load DAC" signal moves the data from memory onto the analog output and holds. The load DAC signal is also the strobe bit signal but with a delay line. Note that, for the DIP switches, the ON position indicates a LOW and the OFF position indicates a HIGH as far as the board address is concerned.

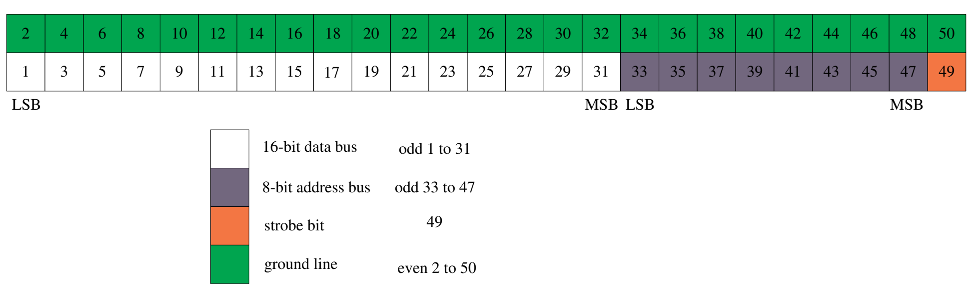



Figure 3: Pin configuration for 50-pin connector.

*Analog Circuit*:

The analog circuit consists of the voltage references and the output buffers. The voltage reference used is the LT1019 from Linear Tech. in the SOIC pkg. We used the 10 V version but it also comes in a 5 V version which may be used with no circuit modification. The other (2.5 V and 4.5 V) may not be used in this circuit without board modification because the DAC requires ±15 V and these lower voltage references can not operate with such supplies. The negative reference is produced with the INA105 in unity inverting mode and has similar stability as the reference itself. The reference inputs use the options given in the DAC7744 data sheet for buffered reference inputs involving the opamp and filter circuit.

The output buffers consist of a precision opamp OPA227 and a buffer line driver BUF634. The buffer boosts the current output of the opamp. The output buffer is able to drive an much as 1/4 Amp, such as required if a $50\,\Omega$ load is used. In practice, since this device is precision and not high frequency, it is not required to terminate the lines with $50\,\Omega$ as it would for high frequency digital lines or RF type sources. However, generally some input load is preferred (i.e. not infinite impedance). A useful receiver circuit appropriate for signals of the sort that this device delivers is given below.

The input filter involving a $10\,\Omega$ resistor and $10\,\mu$F capacitor on most of the analog ICs is to provide power supply isolation for each chip. This is especially important due to the high current nature of the buffer ICs running on the same power supply.

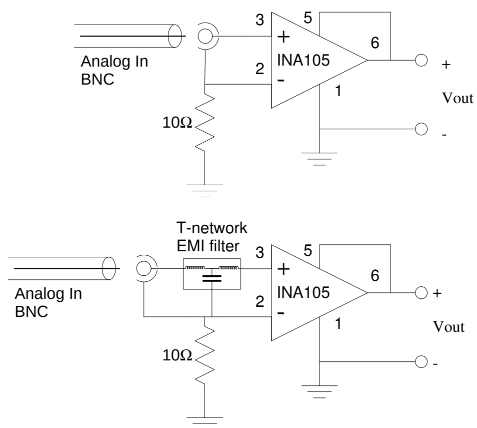



Figure 4: Receiver circuit. These circuits do not appear on the boards described here, but are rather a suggestion for an analog receiver stage of any circuit that the DAC board sources. They use a small resistor $10\,\Omega$ to provide voltage separation between the reference ground of the signal source and that of the receiving device. The INA105 unity gain differential amplifier is a precision device with an input resistance of $50\,\text{k}\Omega$. This provides a load seen by the source and the differential amplifier should reject common mode noise on the signal line. It should also attenuate high frequency ($> 1\,$MHz) noise on the line, but that can also be improved by adding a T-type EMI filter before the amplifier.

*Ground plane comments*:

The ground planes (analog and digital) are entirely separate. The power supply grounds do need to be connected at some location however — but not at two. There is a location for an optional ground plane connection on the back of the board. We connected the power supply grounds near the power supplies and operate them for multiple boards. One should be careful in not forming ground loops. If it is decided to connect the ground planes, one should use a ferrite bead rather than a short. If the power supplies share a ground far from the board – if not this forms a ground loop antenna for RF, but the ferrite has an impedance for such frequencies and should prevent this. We used a ferrite similar to that of the digital IC power supply bypass to connect the planes.

**Modifications for version 2.2**: For some loads, the output buffers have high frequency (several MHz) oscillations, here we add an integration on the output opamp: R58 to R65 $100\,\Omega$ and C76 to C83 $10\,\mathrm{nF}$ which gives a frequency of $1/2\pi RC = 160\,\mathrm{kHz}$. At the moment, we have not tested this — in any case, this can be considered an option, if not used replace R58 to R65 with $0\,\Omega$ resistors. Also added $100\,\mathrm{nF}$ capacitors on BUF supplies C84 to C99.
**Modifications for version 2.1**: The EMI filter (F1 to F8) and protection diode (D1 to D8) were removed from this version. They caused unexpected problems with different values from the original. It is recommended to do any filtering at the receiver device.
**Modifications for version 2.0**: Fix problems on version 1.0.
**Corrections on version 1.0**:

Our first version had the following errors and corrections. These are all fixed on the version given in this paper, these comments are for internal reference.

- Need to invert logic to "Load DAC" pin by adding another inverting gate. Board Correction: On U26, bend pins 2 and 5 up before soldering the chip to the board and then attach them together with a small wire. Use another wire to attach pin 6 to the pad where pin 2 should have gone.

- Need to ground pin 1 of U27 to use the 688 chip. Board correction: connect pin 1 to pin 10.

- Reset DAC pin (pin 17 on U17 and U18) should be connected to +5V not GND for the initial value to be 0V rather than -10V. We did not bother to correct this error on the version 1.0 boards but is fixed for version 2.0.

- Filter capacitors labeled C64 and C65 need to be connected between VrefH and GND and C66 and C67 between VrefL and GND not to the Vref Sense pins. Board corrections: Solder the capacitor to one pad on board and use a small wire to connect to the GND via nearby.

- CS signals go to the reversed DAC, this gives the address table here

| Board Version 1.0 | |
|---|---|
| Address | Output Conn. |
| XXXXX 011 | J1 |
| XXXXX 010 | J2 |
| XXXXX 001 | J3 |
| XXXXX 000 | J4 |
| XXXXX 111 | J5 |
| XXXXX 110 | J6 |
| XXXXX 101 | J7 |
| XXXXX 100 | J8 |

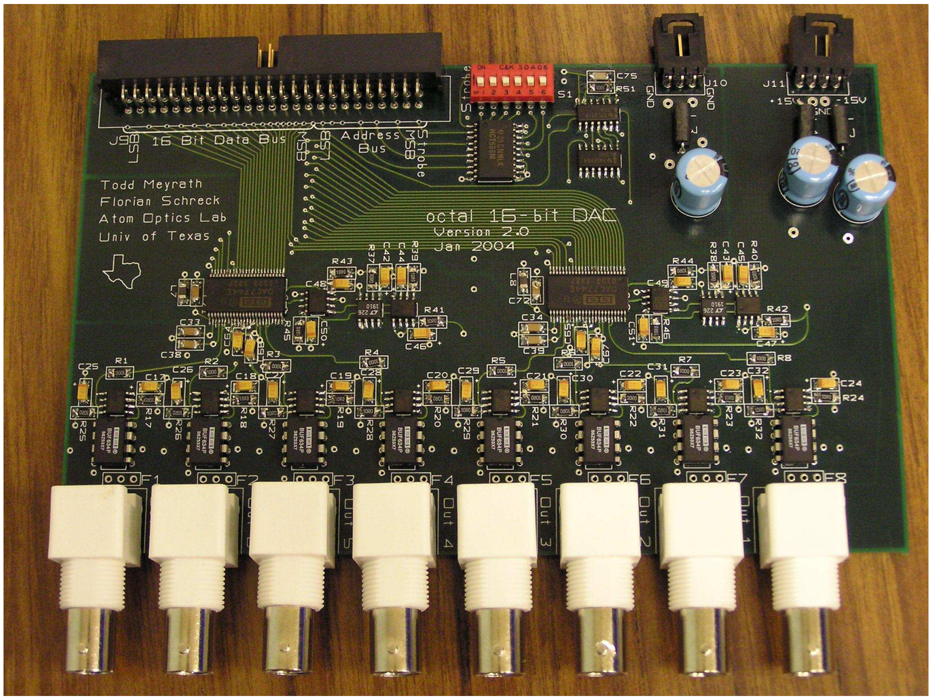



Figure 5: A completed board, lacking only heat sinks glued onto the BUF chips (this is necessary, see above). Note the DIP switches, as shown here, switch 1 is the strobe, 2 is the MSB of the address bus, etc., ON position indicates LOW and OFF position indicated HIGH as far as the local address goes.

Parts

| Qu. | Label | Part # | Manufacturer/Description |
|---|---|---|---|
| 1 | | SMBJ5.0A | Vishay Semiconductor / 5 V unidirectional zener † |
| 2 | | SMBJ15A | Vishay Semiconductor / 15 V unidirectional zener † |
| 30 | R17-R46 | CRCW120610R0FKTA | Vishay/Dale / 10 Ω 1260 pkg resistor. |
| 12 | R1-R8, R47-R50 | CRCW1206100RFKTB | Vishay/Dale / 100 Ω 1260 pkg resistor. |
| 9 | R9-R16, R51 | CRCW12061K00FKTA | Vishay/Dale / 1.0 kΩ 1260 pkg resistor. |
| 6 | R52-R57 | CRCW120610K0FKTA | Vishay/Dale / 10 kΩ 1260 pkg resistor. |
| 8 | R58-R65 | | 100 Ω 1260 pkg resistor. |
| 52 | C1-C32, C36-C37, C40-C51, C64-C67, C73-C74 | T491A106M016AS | Kermet / 10 $\mu$F solid tantalum surface mnt. |
| 25 | C33-C34, C38-C39, C71-C73, C78-C79, C84-C99 | 140-CC502B104K | Xicon / 100 nF cap, 1206 chip pkg. |
| 4 | C60-C63 | 12062R222K9B20D | Yageo / 2.2 nF cap, 1206 chip pkg. |
| 3 | C74, C76-C77 | | 470 $\mu$F electrolytic capacitor 25 V |
| 1 | C75 | | 120 pF cap 1260 pkg. |
| 8 | C76-C83 | | 10 nF cap 1260 pkg. |
| 3 | L1-L3 | EXC-ELSA35 | Panasonic / radial ferrite beads |
| 5 | L4-L8 | BLM31AF700SN1L | Murata / Surface mount ferrite beads |
| 8 | U1-U8 | BUF634P | Texas Inst. / 1/4 Amp high speed buffer, 8-DIP pkg. |
| 8 | U9-U16 | OPA227UA | Texas Inst. / precision opamp, 8-SOIC pkg. |
| 2 | U17-U18 | DAC7744EB | Texas Inst. / Quad 16-bit DAC, 48-SSOP pkg. |
| 2 | U19-U20 | LT1019CS8-10 | Linear Tech. / 10 V band gap voltage ref, 8-SOIC pkg. |
| 2 | U21-U22 | INA105KU | Texas Inst. / Unity gain prec. diff. amp., 8-SOIC pkg. |
| 2 | U23-U24 | OPA2234U | Texas Inst. / Dual precision opamp, 8-SOIC pkg. |
| 1 | U25 | SN74LS00D | Texas Inst. / Quad 2-input NAND gate, 14-SOIC pkg. |
| 1 | U26 | SN74LS14D | Texas Inst. / Hex schmitt-trigger inverters, 14-SOIC pkg. |
| 1 | U27 | CD74HCT688M | Texas Inst. / 8-Bit Mag. Comp., 20-SOIC wide pkg. |
| 1 | S1 | SDA06H1KD | ITT Ind. 6 pos top slide DIP switch, 12-DIP pkg. |
| 8 | J1-J8 | 31-5431-10RFX | Amphenol / BNC right angle receptacle PCB mnt. |
| 1 | J9 | 1-103310-0 | AMP, Tyco Elect. / 50 pos. right angle conn. header. |
| 1 | J10 | 70553-0002 | Molex / 3 pin right angle header power conn. |
| 1 | J11 | 70553-0003 | Molex / 4 pin right angle header power conn. |
| 1 | | 50-57-9403 | Molex / 3 pin mate housing. |
| 1 | | 50-57-9404 | Molex / 4 pin mate housing. |
| | | 16-02-0102 | Molex / female crimp pins. |
| 8 | | 501100B00000 | AAvid / Heat sinks |

Quantity is per board, label is on the PCB, part # is manufacturer number. Most parts obtained from *www.mouser.com*, *www.digikey.com*, or *www.alliedelec.com*.

†One may consider using these as protection diodes in place of capacitors C73, C78, C79.

**Acknowledgements**: The author would like to thank his co-workers on the Raizen Lab's rubidium BEC experiment: Florian Schreck, Jay Hanssen, and Chih-sung Chuu, and of course Prof. Mark Raizen. Florian's experience and suggestions were invaluable on this project. We also appreciate the suggestions and corrections offered by Hrishikesh Kelkar and Kevin Henderson.

# OCTAL 16-BIT DAC

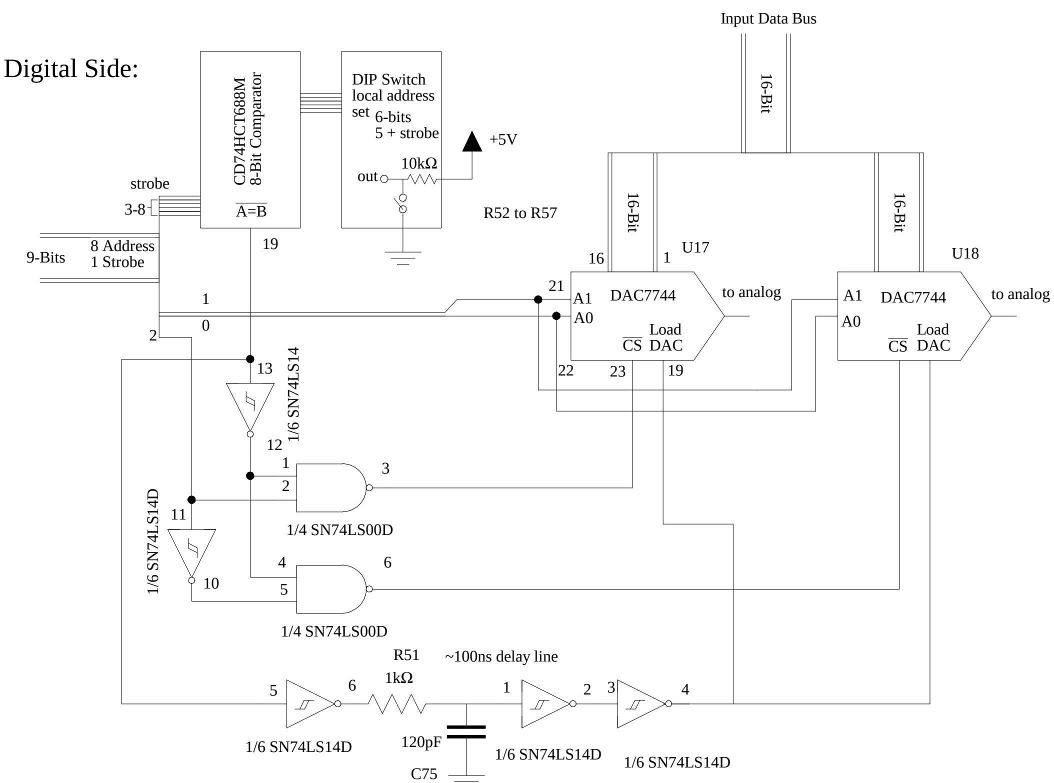
Todd Meyrath
CNLD, Atom Optics
Univ of Texas
Nov 2003
updated v2.2  May 2004

based on DAC7744
from Burr-Brown subsidiary of Texas Instruments

8 channels per board
* 9-Bit parallel input address bus (8-bit plus strobe bit)
* 3 lowest bits select DAC on board, highest bit is strobe
  other 6 bits are board select, with local address set by DIP switches

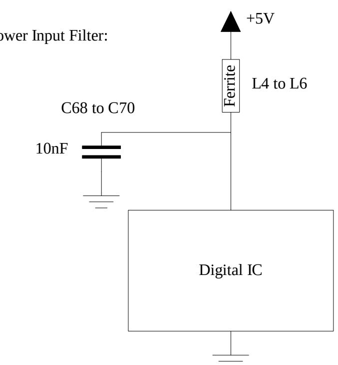
Each Channel:
* 16-Bit accuracy
* 16-Bit parallel input data bus
* analog settling time: 10µs to 0.003%
* +/-10V scale, reference drift 3ppm/C
* BNC outputs
* buffered output drive for 50Ω loads, 250mA max

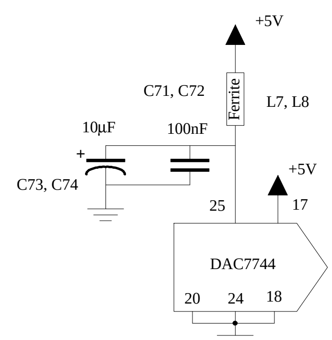
Digital Side:



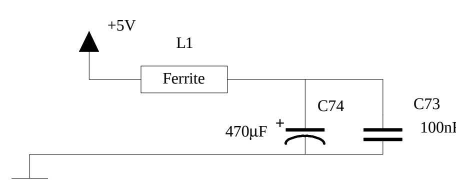

U25 SN74LS00D
U26 SN74LS14D
U27 CD74HCT688M

Power Input Filter:



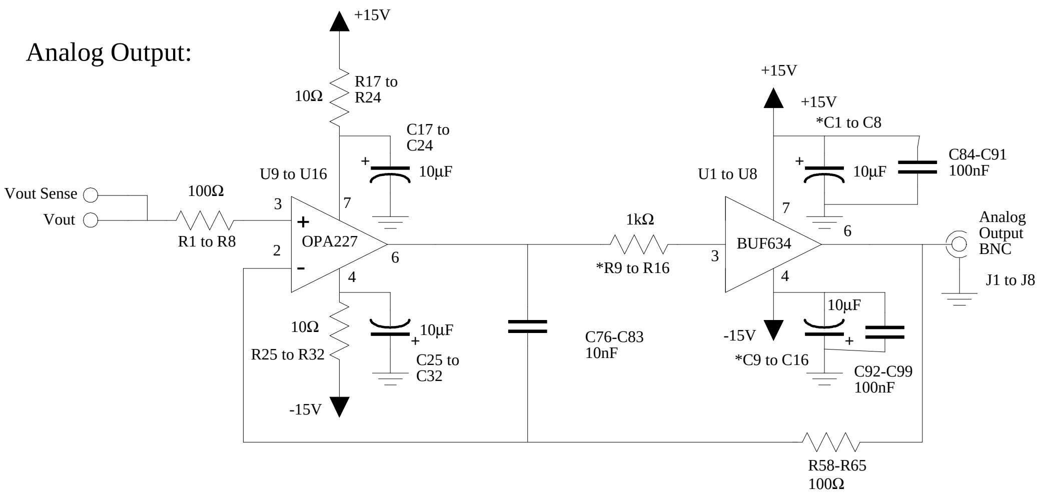




Power Supply Input filter:

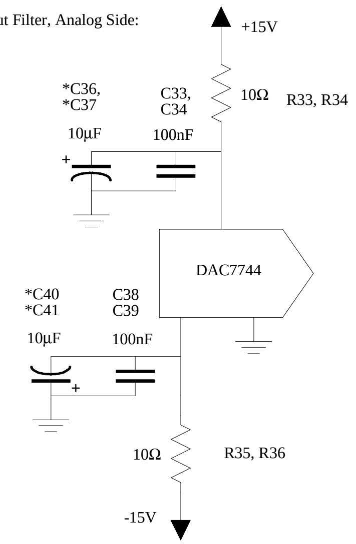



10µF Capacitors shown should be solid tantalum
other capacitors, resistors, and ferrites are 1206 chip package

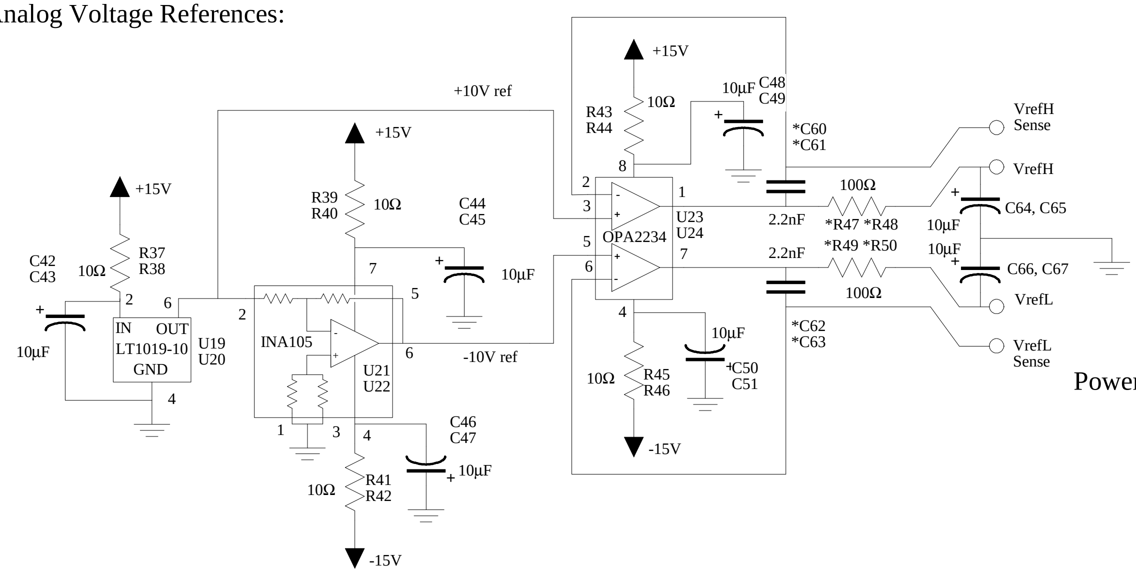
## Analog Output:




DAC Power Input Filter, Analog Side:




## Analog Voltage References:

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## Power Supply Input filter: