

<b>Entry:</b> 001 <b>Date:</b> 1/27/2011 <b>Version:</b> 1.00 <b>Title:</b> Defining requirements
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After the overwhelming success of the Class-D audio amplifier, it was decided to pursue an improved, less experimental version. Some ideas for the revised circuit include using entirely surface mount parts (reduced size and potentially increased performance), a higher supply voltage (increased power output), and an output inductor with a lower series resistance.

Other ideas brought forward for consideration are the use of a different class, such as Class G, Class H, Class I, or Class T. These ideas were rejected due to potential copyright/patent issues and complexity.

<b>Entry:</b> 002 <b>Date:</b> 1/29/2011 <b>Version:</b> 1.00 <b>Title:</b> Initial BOM
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This post is duplicated from the NBitWonder Forums.

After some research, I've arrived at a partial bill of materials.

- MOSFETs - DMN4009
- Gate driver - IRS2004
- Comparator - LM311
- Integrating error amp - TL082

The amplifier will, like the prototype, be a self-oscillating type. My hope is that with proper construction techniques, the operating frequency will be quite high, ideally upwards of 500kHz. To that end, the output filter has been designed as a second-order Butterworth filter with a cutoff of 50kHz when operated with an 8-ohm speaker, a common value for home use. An inductor has been identified with a very low series resistance, which should help efficiency improve over the prototype.

The MOSFETs selected for use this time are cheaper than the IRL520Ns used last time and have a much lower on-state resistance, which should lead to increased efficiency. The MOSFET gate driver is cheaper than the one used for the experiment, but supports a lower drive current and a lower maximum voltage – but at the voltages slated for use in this project, this becomes a non-issue.

The input stages (TL082 and LM311) are slated to be unchanged from the previous iteration, since the parts are already low-cost and well-suited for the task at hand.

Expected power output, based on a +/-18V supply and an 8-ohm speaker, is  $\frac{18^2}{8 \times 2} = 20W$  RMS under ideal conditions. Peak power (ie, turning on one MOSFET or the other and allowing the output filter to reach steady state) is arrived at with  $\frac{V^2}{R}$ ; the extra factor of 2 converts peak power to RMS. To support this power output, the power supply should be capable of delivering  $\sqrt{\frac{20W}{8\Omega}} = 1.58$  amps per channel.

**Entry:** 003 **Date:** 1/30/2011 **Version:** 1.00 **Title:** PCB Layout

Today saw significant work on the PCB layout.

**Entry:** 004 **Date:** 1/31/2011 **Version:** 1.00 **Title:** More PCB Layout

The PCB layout was finished today. A secondary version was created that features RCA input jacks instead of the more compact and lower cost 3.5mm stereo minijack.

**Entry:** 005 **Date:** 3/5/2011 **Version:** 1.00 **Title:** Prototype tweaks

While waiting for the PCBs to come in, I worked on the breadboarded prototype a little bit. I discovered that by changing the resistor and capacitor in the integrating feedback loop to 1M and 0.001uF respectively, power output increased greatly before audible distortion set in. Thankfully, implementing this on the PCB does not require any changes in the layout.

**Entry:** 006 **Date:** 3/6/2011 **Version:** 1.00 **Title:** Continued prototype work

Today, I constructed a duplicate amplifier circuit on the breadboard to have stereo capability, making sure to incorporate the changes from yesterday. Testing with my laptop as a signal source produced good results, though it seems that clipping sets in at a lower level now. My theory as to the cause is that the power supply I am using for testing cannot supply enough current to run both stereo channels at a high volume simultaneously.

With the 'laptop test' complete, I moved the amp to the living room to try it with my TV. Upon powering on the circuit, a loud 60Hz buzz permeated the room. It was determined that the cause of the buzz was a ground loop – the TV and amp were both grounded, and the signal cable between them also had a ground connection. Removing the AC ground from the power supply used on the amplifier solved the problem by eliminating all directly-connected paths between the two circuit grounds.

**Entry:** 007 **Date:** 3/10/2011 **Version:** 1.00 **Title:** PCBs Arrive

The PCBs arrived today!

Rather than dive right in with their assembly, though, I decided to spend some time focusing on the amplifier's packaging. As this is an area I have yet to pay any real attention to on any of my projects, I thought it appropriate to make it a priority for this project. A brief trip to Radio Shack left me with some 4-40 mounting hardware (nuts, bolts, and washers), a 3x5x7 inch plastic project enclosure, a panel-mount audio input jack, and spring-loaded speaker terminals. A few hours spent with a Dremel tool left me with suitably sized holes in the enclosure.

**Entry:** 008 **Date:** 3/11/2011 **Version:** 1.00 **Title:** Power supply assembly

Today saw much of the amplifier's power supply assembly. The transformer was mounted in

the case, along with the power switch, fuse, and line input cord. The appropriate connections were soldered, and the supply was tested. The 24V center-tapped transformer that was selected for this build produced a no-load voltage of 13.6VAC from the center tap to each end of the secondary winding. As this voltage when rectified and filtered will exceed the voltage limits of at least one of the analog components, it may be necessary to drop the voltage slightly with diodes or an add-on regulator if the voltage does not drop appreciably under load.

I also began assembling the main amplifier PCB, but was forced to an abrupt end when I discovered that I made a mistake in the parts order, procuring one too few comparators and the wrong value of output filter capacitors. A parts order was placed with Newark for the missing components.

<b>Entry:</b> 009 <b>Date:</b> 3/12/2011 <b>Version:</b> 1.00 <b>Title:</b> More PCB assembly work
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The PCB was built up to the extent possible today. Still not populated are the various input and output connections (as these are more easily done once mounted in the case), the power filtering capacitors (as they are large and would likely impede access to the smaller-footprinted components).

In light of the unexpectedly high transformer secondary voltage discovered yesterday, some work was done to identify a better way of powering the amplifier. An inexpensive switch-mode controller, the AP34063, was found to be a sub-one-dollar solution to the problem. In a future revision of the amplifier, a single-ended supply of up to 40VDC (or 28VAC followed by a rectifier) will be applied to the amplifier PCB and sent directly to the output MOSFETs. This input voltage will also pass through a low-current switchmode regulator centered on the aforementioned AP34063 which will generate a 12VDC control supply to operate the input stages and MOSFET gate driver IC. This will allow for a greater supply voltage, boosting output power; additionally, the power supply requirements will be greatly relaxed.

<b>Entry:</b> 010 <b>Date:</b> 3/13/2011 <b>Version:</b> 1.00 <b>Title:</b> Single-supply amplifier
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An initial design was drawn up for the single-supply amplifier. It is now included in the github repository for the project, though it is far from done.

<b>Entry:</b> 011 <b>Date:</b> 3/14/2011 <b>Version:</b> 1.00 <b>Title:</b> Single-supply amplifier progress
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Some work was done on component placement for the single-supply board layout. Additionally, the MCP14628 was identified as a potential gate driver for the new amplifier version. It is similar to the IRS2004 currently in use, but with much lower propagation times between a gate command on the input and an action on the output. Its deadtime is variable and is automatically configured based on the characteristics of the attached MOSFETs, which is far ahead of the fixed 520ns deadtime on the IRS2004. It has been added to the Eagle library.

The downside of using the MCP gate driver is the limit on its bootstrap voltage pin – 35v. This means that the supply to the amplifier cannot exceed 30VDC, limiting power output to approximately 15W. If the output sound quality is better, though, this is probably an acceptable tradeoff to make. Otherwise, a similar part from National Semiconductor exists – the LM5104 – but its cost is about double the MCP part at roughly 3 dollars.

<b>Entry:</b> 012 <b>Date:</b> 3/16/2011 <b>Version:</b> 1.00 <b>Title:</b> Single-supply amplifier progress
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More work was done with regard to component placement on the single-supply version of the amplifier tonight. It is believed that component placement is now final, more or less.

Additionally, an experiment was conducted with bridging mode on the breadboard. Recognizable sound was emitted from the speaker, but it was highly distorted. It is believed at this time that the output filter's capacitor was connected between the positive speaker lead and the then-irrelevant ground instead of across the speaker terminals. Further tests will be conducted as time allows.

Another version of the single-supply layout is in progress, too. This secondary version features bridged outputs for each channel, allowing a theoretical 56W output per channel with a single-ended 30V supply. If further breadboard tests with bridging (and eventually, single-supply bridging) are successful, this PCB layout will be furthered. For now, it will be set aside.

<b>Entry:</b> 013 <b>Date:</b> 3/19/2011 <b>Version:</b> 1.00 <b>Title:</b> Progress on amplifiers
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The missing parts for the dual-supply amplifier prototype arrived yesterday. Unfortunately, I rushed through the order process last week and requested the DIP-8 version of the LM311 instead of the SOIC-8 version. Another order was placed and should hopefully arrive shortly. Once I finally have a part with the correct footprint, this amplifier should come together very quickly. I was, however, able to solder down the new filter capacitors, so that is done.

I spent some more time working on the single-supply amplifier layout. It is now complete – at least as a first draft – and has been placed in the git repository.

<b>Entry:</b> 014 <b>Date:</b> 3/22/2011 <b>Version:</b> 1.00 <b>Title:</b> Magic smoke
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The replacement comparators arrived today, and they were installed. The board then had its final components added and peripheral connections to the case-mounted connectors completed. A brief power-up test revealed that nothing major was wrong. The MOSFET gate drivers were running quite warm, but they were within specs outlined in the datasheet. The power supply was measured to be a bipolar 19VDC for 38VDC total across the entire board. The expected value was more like 33V, but this was deemed to be within spec due to the lightly-loaded power transformer.

The amplifier was then connected to a signal source (my TV) and speakers for its first real test. The amplifier performed flawlessly for several minutes, but then suddenly ceased to

function and simultaneously sent a large amplitude 60Hz buzz to the speakers. Subsequent disassembly revealed a "burnt component" smell and a MOSFET solder joint that appears to have been reflowed.

The hypothesized failure mode is that a brief power glitch on the AC mains (due to my refrigerator turning on at the exact moment of amplifier failure) temporarily boosted the amplifier supply voltage sufficiently to over-volt the gate of the MOSFET – which has a maximum  $V_{gs}$  of 20V – and permanently short it. This would explain the 60Hz hum of the power supply being directly coupled to the speakers as the transformer struggles to boost the output voltage to its designed operating point. At this time, it is believed that replacing the power transformer with a lower-voltage output model and replacing the damaged MOSFET will fix the problem with this particular amplifier build.

As time allows, development will continue on the single-supply version of the amp. It is believed that by regulating a few crucial control voltages, disasters like tonight's can be avoided in the future. Until the amplifier failed, its output sound quality was noticeably better than the breadboarded version of the amplifier, implying that the basic is sound and need not be abandoned.

<b>Entry:</b> 015 <b>Date:</b> 4/2/2011 <b>Version:</b> 1.00 <b>Title:</b> Single-supply amplifier
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A single-supply amplifier prototype was built up on a breadboard today. After much tweaking of the feedback network to ultimately include a DC-blocking capacitor and adding a second gate driver and half-bridge driven 180 degrees out of phase with the first, a single-supply bridged amplifier is now functional.

Since its modulator is driven from 5v (instead of 12v-15v as in the dual supply version), I was able to connect a logic analyzer to the generated PWM signal. The switching frequency using reasonably compact construction techniques is approximately 250kHz.

It was found that operating the amplifier near peak volumes from the signal source (an iPod) creates issues with MOSFET gating that may temporarily short-circuit the power supply. This will have to be addressed before a production version is completed – but it is believed that switching to the new gate driver with much shorter dead times should improve this.

Schematics and updated board layouts will follow as time allows.

<b>Entry:</b> 016 <b>Date:</b> 4/4/2011 <b>Version:</b> 1.00 <b>Title:</b> Single-supply amplifier
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Some more experimentation was carried out with the breadboarded bridged single-supply amplifier. It was determined that – unexpectedly – using a 13V supply produced louder output than a 26V supply. I hypothesize that this is due to the feedback network and its (surprise!) 13:1 ratio between output and feedback. Changing this to something along the lines of 26:1 or 30:1 should boost output at higher supply voltages.

I also read up on ways to improve the noise performance of the amplifier. The LM311 com-

parator datasheet offered a number of suggestions for making its output transitions faster and more decisive (so to speak), which involved shorting two adjacent but otherwise unconnected pins on the IC. This was done on the breadboard and it seems to help ever so slightly. Additionally, the datasheet suggests placing a small capacitance directly between the comparator input pins. A footprint for a suitable cap will be included on the next PCB revision, though the part may not be populated.

<b>Entry:</b> 017 <b>Date:</b> 4/6/2011 <b>Version:</b> 1.00 <b>Title:</b> Single-supply amplifier
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I worked on the single-supply bridged layout some more this evening. Upon realizing that the board was nearly twice the size of the previous revision, I made the executive decision to replace the switching regulator with a linear regulator to save considerable board space. This should be an acceptable tradeoff, since the average current draw on the 5V rail will be on the order of 50mA - 100mA. Large current spikes will be drawn for 40-50ns while the output devices switch, but this will be twice every 4us, for a duty cycle in the sub-one-percent range. Since the maximum input voltage is limited to 30V by the gate driver anyway, this does not deprive us of output power.

I also made some headway on boosting power output at higher supply voltages. Replacing the 1k resistor in the feedback network with a 560-ohm resistor seems to have made all the difference. I can now advance the input volume quite far before the onset of clipping. If my understanding of the circuit is correct, this reduces the amount of the output signal that is integrated with each cycle, allowing the current in the filter inductor to increase to a higher value and drive more power through the speaker.

On the topic of last weekend's tests that resulted in shorting the power supply, it is now believed that the inductor was entering saturation. On average, the output voltage is zero (as is the inductor current). HOWEVER, the inductor current can rise to two or three amps during the highest part of the modulating waveform. Suppose for instance the H-bridge is currently conducting such that 26V is across the output. If the capacitor voltage is 0 and the switching frequency is 250kHz (typical measured values), the inductor current increases to 2.8A near the end of the switching cycle, which is the saturation current for the chosen inductor. An inductor in saturation is characterized by an increase in current with no corresponding increase in flux – so it looks like a dead short. At least, this is what I think the amp was doing last weekend.

<b>Entry:</b> 018 <b>Date:</b> 4/7/2011 <b>Version:</b> 1.00 <b>Title:</b> Bridged single-supply amplifier analysis
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Having recently acquired a basic oscilloscope, I was able to take a few measurements concerning the amplifier's operation. For a 0.560Vpp input, the amplifier produces an output of 19.2Vpp. For this test, the input signal was a 1kHz sine wave from my computer sound card.

I was also to determine the point at which the amplifier starts clipping – the point that corresponds to the maximum output power with good sound quality. This point occurs



at 20Vpp, or at 10V on either side of the neutral point, with a 26V supply. Because the output stage is an H-bridge, this corresponds to a duty cycle of 0.69 from the output of the comparator for the positive peak of the clipping waveform. Additionally, 10V across the speaker corresponds to a load current of 1.25A. The ripple current through the load at this point can be determined as follows:

We know that the voltage across the inductor can be expressed as  $(V_{\text{supply}} - V_{\text{out}})$ , or here, 16V. The voltage across an inductor can be expressed as  $V_L = L \frac{di}{dt}$ . Rearranging and solving for  $dt$ , we arrive at  $\frac{V_L dt}{L} = di$ . Here,  $dt$  is the time in which voltage is rising, or the product of the duty cycle  $k$  and the switching period  $T_s$ , so  $di = \frac{V_L k T_s}{2L}$  since the total current rise is twice the ripple current. Substituting our circuit parameters, we arrive at a ripple current of 0.67A. Adding this ripple value to the average value for this point gives a maximum inductor current of 1.92A, which approaches the saturation value of 2.3A for the inductor in use in the circuit.

The other explanation is that my power supply is underpowered for this application. The supply is capable of a bipolar 13V output unloaded, and the transformer is rated for some 800mA. As an experiment, I connected an 8-ohm resistor between its 13V terminal and its ground terminal, and the output voltage dropped from 13.2V to 8.72V. This may partially explain the difficulty I am seeing. I will try to find a more powerful supply in the 26V range for further testing. (I have a couple of supplies capable of high current at 12V, but I'd really like to test the amp near the edge of its range to hopefully foresee any self-destruction problems like the ones previously experienced.)

Oscilloscope screen captures to follow.

<b>Entry:</b> 019 <b>Date:</b> 4/8/2011 <b>Version:</b> 1.00 <b>Title:</b> New inductor
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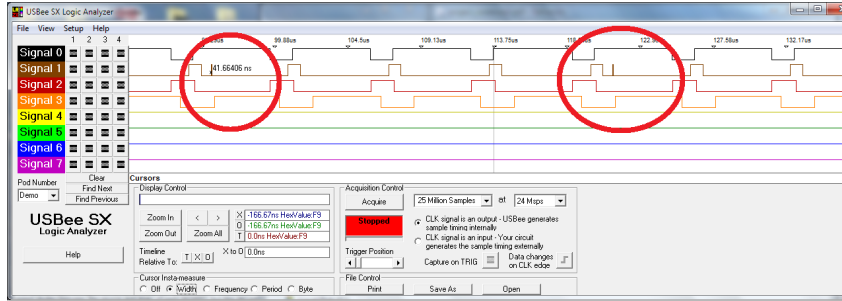
I replaced the inductor I had been testing with (which saturates at 2.3A) with one used on a previous project. The replacement inductor has a saturation current of 4.9A. Sadly, the low-voltage clipping and temporary power supply shorting behaviors remain. I would like to blame transistor dead times, but I have no good way to prove this at present.

<b>Entry:</b> 020 <b>Date:</b> 4/9/2011 <b>Version:</b> 1.00 <b>Title:</b> Changing the analog front end
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A lot of amp work was done today.

First, I hooked up the logic analyzer to the gating command signals (from the comparator) and to the bottom MOSFET gates. The upper gates were not included due to their need for a floating supply and the 5V maximum input of the logic analyzer. It was discovered that at high input levels, the bottom MOSFET on a given channel would turn itself on while the top MOSFET was conducting, leading to the shoot-through condition. I tried to stop this from happening by placing reverse-biased high-speed diodes between the source and drain of each MOSFET, but this did not solve the problem. It may be necessary to get a "stronger" gate driver that can sink multiple amps of current to keep transistors turned off when they're

supposed to be off.



Noticing that the amp could become unstable at times with the DC blocking capacitor in the feedback loop, I rewired the analog front end to eliminate the need for this capacitor. Instead of powering the input op-amp and comparator off of 5V as I had been doing, I now power them off of the full input voltage. The input is limited to 30V by the gate driver, so no specs should be exceeded in doing this. Additionally, the comparator output is open-collector, so logic level interfacing between the gate driver and comparator is done inherently and no special attention is needed to accomplish it. A second op-amp channel is still used to create an internal low-current  $\frac{V_{CC}}{2}$  rail, but this rail now operates at half the supply voltage instead of 2.5V.

A new problem was introduced, though. If the requested output is greater than what the MOSFETs can supply for any period of time, the amplifier can stop oscillating. Luckily, the failure mode happens such that one half-bridge stops conducting completely, so a speaker-destroying DC current does not appear across the speaker. This issue will have to be dealt with prior to ordering amplifier PCBs. One potential correctional measure is to include an additional triangle-wave based modulator.

**Entry:** 021 **Date:** 4/10/2011 **Version:** 1.00 **Title:** More debugging

I spent some time today reviewing the gating circuitry for the MOSFETs. It dawned on me that one of the gate drivers was driven with an open-collector signal (so there was a pull-up resistor in the signal path, leading to potentially slow turn-on times) and the other was driven with a push-pull signal from an inverter. To equalize the two delays, two XOR gates were used. The open-collector signal connects to both 'A' inputs. The first gate's 'B' input is connected to 0v to make a pass-through gate, and the second gate's 'B' input is connected to 5v to make an inverter.

Unfortunately, this did not fix the problem. The amplifier can still output a negative voltage with a magnitude equal to the power supply voltage, but the positive voltage magnitude is limited to 10V or so.

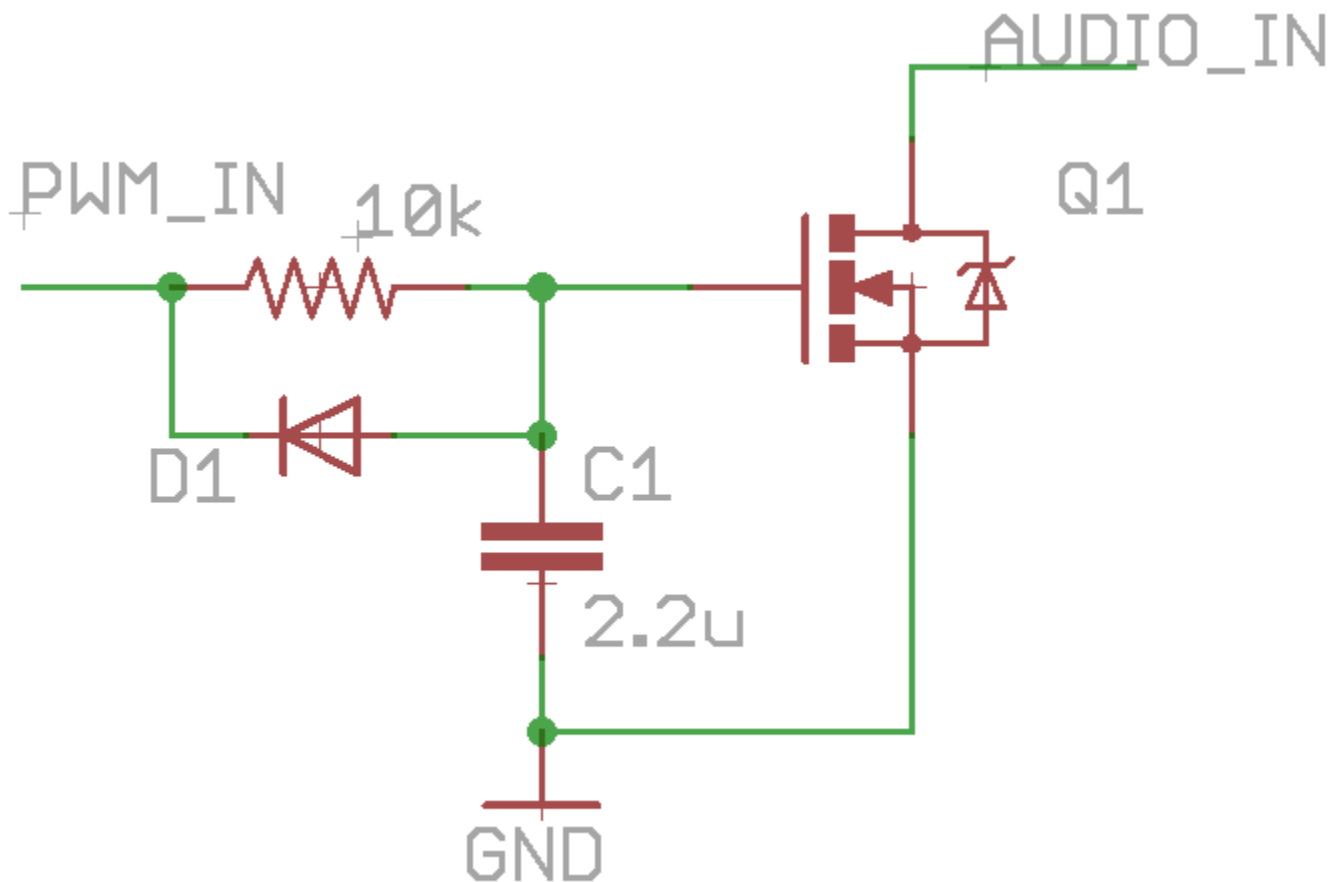
**Entry:** 022 **Date:** 4/13/2011 **Version:** 1.00 **Title:** Duty cycle limiter and gate drive mods

After much head scratching, I arrived at a breakthrough on the the amplifier clipping prob-



lem. I determined that the high-end clipping was due to the "top" MOSFET's bootstrap capacitor running out of charge during prolonged operation with the top switch turned on. This condition manifested itself by having the top MOSFET on the "positive" channel (the one from which feedback is taken) become quite warm and stop conducting during prolonged "on" periods, that is, when the gate drive signal commanded that MOSFET on.

To fix this, the bootstrap capacitor value was first increased to 1uF, after which a marked increase in available conduction time was noted... but the problem persisted at times. Rather than increase the capacitor arbitrarily, an alternative solution was developed: a duty cycle limiter.



The limiter consists of an RC circuit connected to an N-channel MOSFET. The resistor in the RC circuit is connected in parallel with a diode biased such that it conducts only on the "low" edge of a PWM waveform. The circuit's capacitor is connected across the MOSFET's gate and source terminals such that it delays the turn-on of the MOSFET. When the PWM waveform goes high, the capacitor begins to charge via the resistor. If the PWM signal goes low before the MOSFET turns on, the circuit operation is unchanged. If, however, the PWM signal stays high long enough to charge the capacitor, the MOSFET fires and pulls the amplifier channel's audio input to ground via a resistor (not pictured). When this signal goes

to ground, the amplifier tries to compensate by reducing the output voltage, turning off the PWM signal and the problem transistor. The duty cycle limited capacitor then discharges, and the circuit automatically resumes normal operation.

It is believed that this circuit will fix nearly every issue this breadboarded prototype has been having. Before ordering a final PCB, though, I will wait until I've had a chance to validate desired operation of the MCP14628 driver IC, which I hope to use in the new amplifier version due to performance and availability concerns with the old driver.

<b>Entry:</b> 023 <b>Date:</b> 4/26/2011 <b>Version:</b> 1.00 <b>Title:</b> New gate drivers
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I put together a simple PCB I laid out based on the MCP14628 synchronous buck driver. The board features the driver, two MOSFETs, and a couple of caps; that's it. It turns out that the gate driver switches sufficiently fast that the breadboarded power supply (with copious decoupling) can't supply sufficient current pulses to operate the switch! That is to say, the circuit sort of works but not really. In order to tell for sure if this new gate driver will work as intended, it will likely be necessary to lay out a PCB for the amp without knowing beforehand if it will work. Hopefully the product, experimental or not, will be ready in time for Maker Faire North Carolina, coming up in about 6 weeks.

<b>Entry:</b> 024 <b>Date:</b> 4/28/2011 <b>Version:</b> 1.00 <b>Title:</b> New gate drivers
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I tested the gate driver breakout board some more, and managed to short something out with a slip of the DMM probe while taking measurements. The magic smoke was swiftly released... but the gate drivers appear to do the trick when suitably large reservoir caps are present. Thusly, I began a revised board layout incorporating all the changes made to the breadboarded version.

<b>Entry:</b> 025 <b>Date:</b> 4/29/2011 <b>Version:</b> 1.00 <b>Title:</b> New PCB layout
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I worked on the revised schematic and board layout today. Thirty-eight airwires remain, down from approximately 160 at the outset of the layout. Hopefully, this layout will be completed this weekend or soon after.

<b>Entry:</b> 026 <b>Date:</b> 4/30/2011 <b>Version:</b> 1.00 <b>Title:</b> New PCB layout
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Zero airwires achieved! After a peer review, the design will be sent off for fabrication. This should hopefully happen within a couple of days.

<b>Entry:</b> 026 <b>Date:</b> 4/30/2011 <b>Version:</b> 1.00 <b>Title:</b> New PCB layout
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The PCB layout is done. I will try to have it reviewed tonight and ordered shortly thereafter.

<b>Entry:</b> 027 <b>Date:</b> 5/4/2011 <b>Version:</b> 1.00 <b>Title:</b> PCBs ordered
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I ordered a copy of the latest PCB revision tonight from Advanced Circuits.

<b>Entry:</b> 028 <b>Date:</b> 5/9/2011 <b>Version:</b> 1.00 <b>Title:</b> Parts ordered
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Parts for the newest PCB revision were ordered tonight. Total parts cost (before tax and shipping) was USD 32. Not bad for something that can theoretically produce 50W per channel.

<b>Entry:</b> 029 <b>Date:</b> 5/17/2011 <b>Version:</b> 1.00 <b>Title:</b> Single-supply amp assembled
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Amplifier parts arrived last week, and the PCB arrived yesterday. This could mean only one thing – it was time to assemble the PCB!

I am pleased to report that assembly went very smoothly, taking approximately 90 minutes to completely populate the board. Once powered up, the amplifier worked beautifully and did not show any tendency to emit smoke. The only complaint I have is that the 5V regulator becomes quite warm under normal operation, but it is my own fault for using a linear regulator in this capacity. A switching regulator would have been much more efficient, but it also would have added to the cost significantly and likely would have degraded audio quality. A small heatsink should fix this problem quite readily.

A demonstration video has been posted to YouTube, and photos of the completed PCB can be found on our Flickr page.