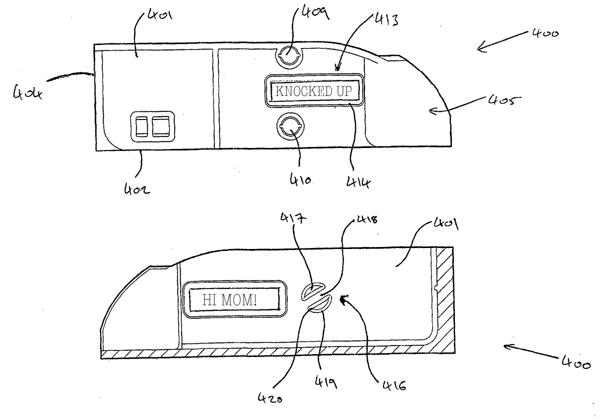
6 Reversing a Pregnancy Test; or, Bitch better have my money!

by Amanda Wozniak

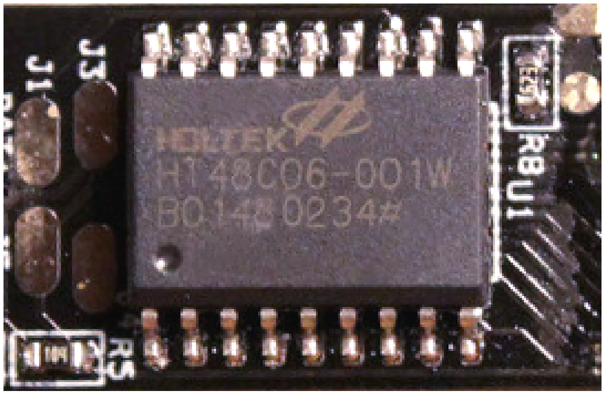
The adventure started like most adventures do—in a dark bar near a technical institute over pints of IPA. An serial entrepreneur plied me with compliments, alcohol and assurances of a budget worthy of my hourly rate to take an off-the shelf device and build a sales-pitch demo in support of his natal company's fund-raising and growth plan. The goal was to take approximately zero available fabrication resources other than myself and spend a couple of months to make a universally approachable, easy to use demonstration prototype for a (now utterly defunct) startup's flow strip technology with a hack-a-thon patented Internet-of-Things interface. The target was an entry straight out of PC Magazine's *The Secret World of Embedded Computers*, the thing no active neighbor should be without—a handy-dandy off the shelf CVS digital pregnancy test.



6.1 Fast, Cheap, and Easy

Head on down to your local pharmacy, and virtually every store will carry a nifty brand of digital pregnancy tests. All of these tests are basically identical (inside and out), and the marketing strategy is simple. Humans are bad at reading analog inputs, so when your time comes, let technology ease your mind whether you, the user is stressed to the breaking point trying to get pregnant or if you're in the boat of desperately hoping you're sterile. "Oh god, it's been three seconds. Or minutes? Wait? What happened to space time. Is there one blue line? Two? I feel faint. Fish? Fuck! I'm pregnant with mutant fish babies."[28]

Now, it doesn't matter which brand you buy for this exercise—as far as I can tell, they're all based on the same two-chip solution built around a Holtek HT48C06 microprocessor. And you can guess at the function without cracking the case – just go buy one (for extra bonus points, look as underaged as possible) and look at the test strips themselves.



Remember, this OTS technology is extra cool because back in the day, instead of peeing on a stick, women suspected of pregnancy[29] had to have their urine injected into a rabbit in order to assess pregnancy before the onset of "the quickening." If you think it's hard telling the difference between '+' and '–', you definitely haven't had to divine your future livelihood from the appearance of leporid entrails. And for extra bonus by the Theory Of Cyber-Extension, every time you use a digital pregnancy test, a cute bunny Tamagotchi is saved from certain death.

6.2 Basics of the Test

Each strip has an absorbent area (that you pee on) and a clear window where the test results show up. One stripe is a control stripe that 'fires' (changes color) in any liquid from water to bourbon, and the other one is a test stripe that only fires when sufficient concentrations of the hormone hCG are present

[28] The mutant fish baby thing is kind of true according to developmental biology, but that's not really our focus today.

[29] *Fun fact*: Eve was the first hacker and Cain was her first 0-day. Humankind is the ultimate Trojan. Since Cain was such a dick in the Biblical sense, the hacking community has carried his mark of social stigma until this very day.

in the fluid sample. (hCG stands for Human Chorionic Gonadotropin, named because scientists snicker at words like "gonad.") You can use the strips without the digital tester, because all you're being sold is a device that will load in one of the basic strips, and monitor the control and test stripes, and return three results: ERROR, NOT or PREGNANT. It turns out that $50 and getting at least one pregnant woman to pee on a test strip can end up for an entertaining couple of evenings at the old workbench.

Following these instructions, with enough time, patience and abstinence, you'll be able to make your own legitimate-looking pregnancy test that works on men and women alike! Or jazz it up to say "`HI MOM`" in no time.

6.3 Teardown

To open the case of a digital pregnancy test (DPT), take a nickel or quarter, place it in the detent in the injection molded case, and gently twist. The model of DPT I did most of my work with was the generic "CVS Clear Results," test – the mechanical specifics may vary from brand to brand, but the nicest part of the cheap injection-molded plastic is that the shell parts are universally thin-walled and toleranced to snap-fit together, which makes it easy to snap them apart without visibly damaging the case.

Inside that case, there will be a circuit board that has another multi-piece injection-molded assembly of ABS plastic, press-fitted into mounting holes on the PCB. This is the test strip alignment/ejection mechanism.[30] For my purposes, I removed this semi-destructively, by twisting off the retention pins on the back side of the PCB. I wanted to save the housing for when I rebuilt the test with my own internal electronics, to be virtually indistinguishable from the stock pregnancy test but with added entrepreneurial functions. This strategic re-use of injection molded parts and hard-to-design mechanisms adds that special professional flair to demonstration prototypes.

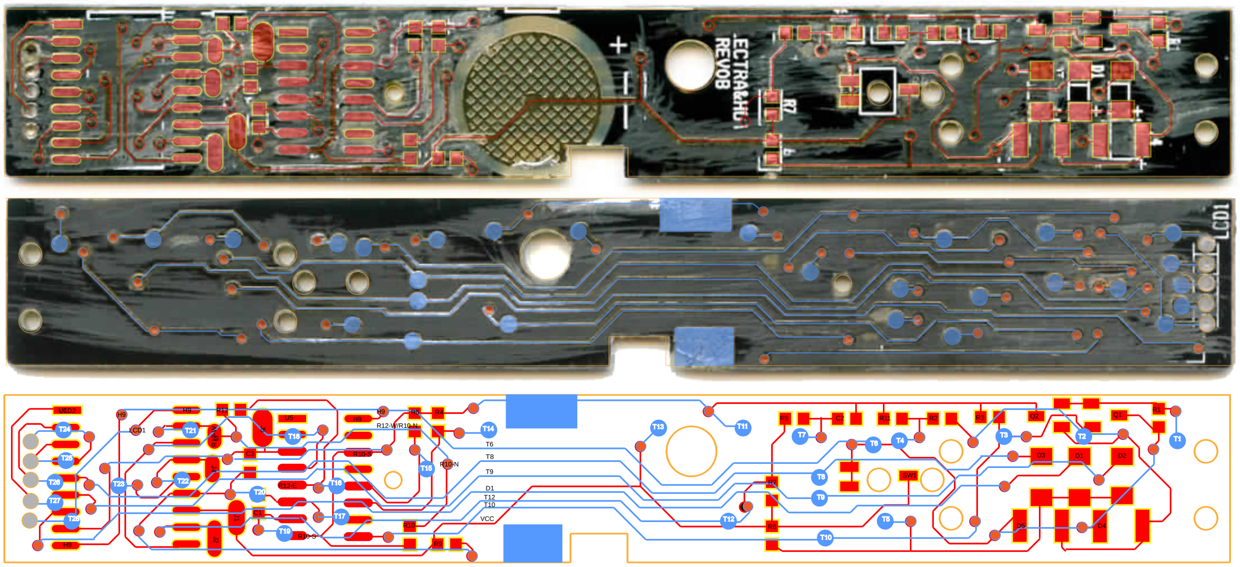
Once you've got the holder off, you'll uncover an activation switch and the analog optical sensor (made of two photodiodes and three LEDs), a PLL (used only for its voltage-controlled oscillator) IC, the aforementioned Holtek HT48C06, a 3V battery and a custom LCD. You can either look up the battery type to confirm it's 3V, or just read the CE-mark label on the outside of the DPT that lists the part number, lot data, confirmation that this test is made by SPD GmbH out of Geneva, Switzerland (made in China), and that the test runs on 3V DC. Safety first, kids. Also convenient: if you peel up this label, you'll see holes in a pattern of the case that line up with un-tinned pads on the PCB. These are the calibration and test points for the Holtek, which means if you prefer firmware reverse-engineering to hardware reverse-engineering, you can go fiddle with the insides *from* the outside.

By the by, that label isn't tamper-evident. You can easily replace it. Don't get any ideas!

6.4 Schematic

Flick the little button, and you'll see the whole test light up (with or without a strip). The LEDs strobe, the LCD thoughtfully blinks its "thinking" icon, and a scope or DMM will show plenty of pin activity until the test errors out because you just set it off

[30] `unzip pocorgtfo10 pregpatent.pdf`



without a valid test strip. I could have started probing there, but I realized that an optical test requires a dark environment, and I wanted to bring my test wires out through the conveniently placed unit-test-and-programming holes on the case. My ultimate goal was to test the unit under multiple conditions to determine the internal logic. That meant making a schematic.

I don't enjoy tracing out circuits with dark soldermask, and the DPTs are relatively cheap, so I gathered up the pinouts for each IC and then did my physical net trace using graphic design tools.

Step 1. Desolder all components from the PCB.

Step 2: Scrub the pads with solder wick to get them nice and flat.

Step 3. Using a razor blade or fine-grit sandpaper, sand off the soldermask with loving attention on both sides of the PCB.

Step 4. Scan the PCB with high contrast.

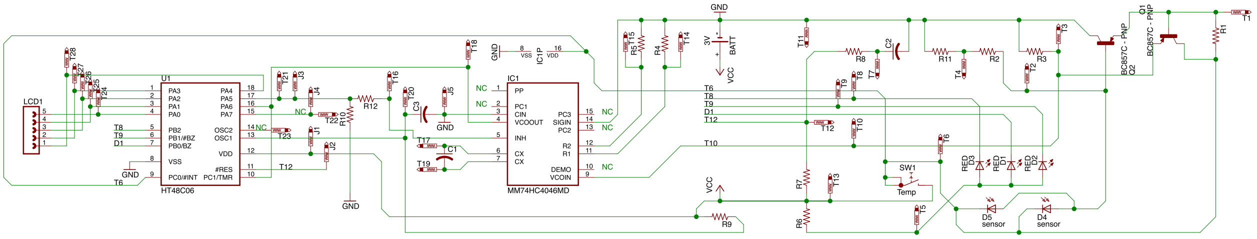
Step 5. Import the scans into an illustration tool of your choice. Color code the top vs. bottom scans to match your preferred layout scheme. Drop circles on the vias—*first*. Then add the IC and passive pins. Then add your traces. Use the vias to register the two images on top of one another for a single layout trace.

Step 6. Annotate the trace with the reference designators from an intact PCB. Add your own net names and pin labels. Use this to build a reference schematic.

6.5 Let's Skip the Firmware

Let's walk through what this sweet little circuit is up to.

First off, the Holtek micro is always on, albeit in sleep mode. The battery is sized for the shelf life of the device plus a couple of uses (three strips ship with each one). When a test strip is placed in the tester, it mechanically triggers the switch which a) flags an interrupt to the microcontroller to wake it up out of sleep mode and b) enables power to the PLL and sense circuitry that would not otherwise be powered. If you remove the test strip mid-test, it cuts power to the PLL and the micro will error out, making it a bit of a pain to work with. Meh,



meh, power-saving feature and fault reporting during foreseeable misuse.

Once all supplies are up, the Holtek samples the state of the optical sensor four times a second for twenty iterations, averaging the samples. In order to sample the test strip, the Holtek drives the LEDs and then reads back the output state of the photodetector, using the voltage-controlled-isolator (VCO) sub-function of that phase-lock-loop IC. The role of the VCO is to convert the analog voltage from the photodetector into a square wave for easy edge counting. Higher voltage implies a higher frequency of edges. Because the micro controls the LED excitation timing, it can easily tell by edge counts what color test strip the LEDs might be illuminating. It's pretty nifty.

Because I wanted to build new electronics to fit inside the case of the original DPT and reproduce a function similar to the original hardware and firmware, I dove into the deeper specifics of how the DPT detects whether one or two blue stripes show up in that plastic clear-view window. The secret is stereoscopic vision enabled by time-division multiplexing and the physical layout of the optosensor. The three LEDs are interdigitated with two parallel photodiodes that are the base current sources in a PNP common emitter amplifier (D4, D5, Q2). The Holtek enables each of the 3 LEDs (D1, D2, D3) sequentially using a 25% LOW duty cycle waveform at 10kHz. The LEDs are strobed in a round-robin fashion and the Holtek samples the result via the VCO.

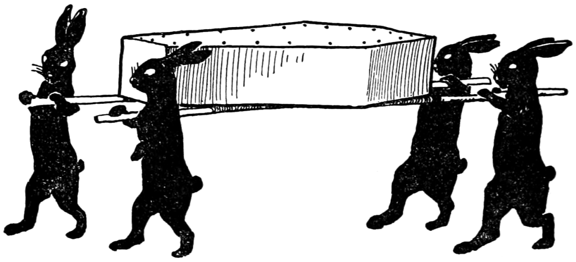
When any one of the three LEDs is strobing, the induced current in the photodiode causes the filter cap on the output of Q2 to charge. The LED's light causes charging, while discharging occurs while the LED is off. Because the Holtek excites the LEDs intermittently, the output of the photodetector is a sawtooth wave. The period of the sawtooth is the LED drive interval, while the peak and trough of the sawtooth wave correspond to the colorimetric intensity of the test stripe that appears and/or the amount of mis-alignment between the photodetector and the LED array.

But how does this produce stereoscopic vision, you ask?

For the same background test strip, when D1 is on, the sawtooth peak-to-peak amplitude will be different than when D3 is on, giving the sensor some ability to resolve spatial light sources. Because the LEDs are independently addressable, it also means that the Holtek can discriminate between a colored stripe hanging over D5 (stripe #1) versus one hanging over D4 (stripe #2). Also, all apologies for the fact that the reference designator order for the diodes makes no physical sense. It's not how I'd design the board, but it apparently took eight revisions for the manufacturer to get this far.

6.6 Schrödinger's Rabbit

Okay, so if you're pregnant, it works like this.



Just kidding, folks—here's what the DPT is doing.

	Photodetectors			Test Stripe	
	D3	D1	D2	ST1	ST2
PREGO	L	H	L	CNTRL	PREGO
CNTRL	L	H	H	CNTRL	...
ERROR	H	H	L	...	PREGO
BLANK	H	H	H	...	...

Remember that a high PD voltage implies more edges counted by the Holtek per excitation cycle. The Holtek uses this *and* sequencing to tell if you're pregnant. Based on the chemistry of the test stripe, the test expects the CNTRL stripe to fire first. If only the CNTRL stripe fires—congratulations, you aren't pregnant! Again, due to chemistry, the PREGO stripe ought to always fire second, if at all. If the stripes fire out of order, that's an error. If the PREGO stripe fires but the CNTRL stripe doesn't, that's an error. If no stripe fires, that's an error.

The factors that contribute to setting the DETECT vs. NO-DETECT threshold for "how many edges do I expect to count if the rabbit died" are (1) the distance from each of the three LEDs to each of the two sensors, (2) the intensity of the LEDs, (3) the color of the LEDs (as that corresponds to the sensitivity of the sensors for a given wavelength of light), (4) the placement of the stripes (if they appear) with respect to the two photodiodes, and (5) the color of the stripe and the saturation of the stripe. Because process controls on LEDs are fucking horrible, each test has to be individually calibrated after assembly.

But that's good news for us!

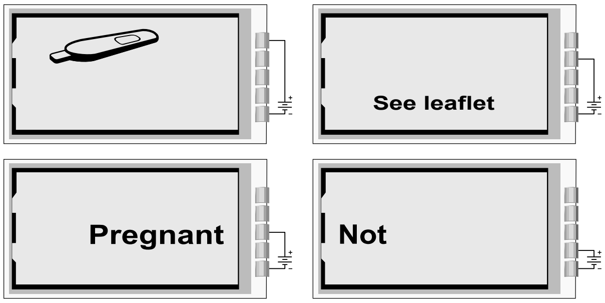
6.7 Hands-On Hacking

Let's be honest, you don't want to come up with a new set of guts to shove into the case of a digital pregnancy test relabeled `0xBEEF` and `0xCAFE` for maximum entertainment and confusion to potential investors! You just want to have fun with the available raw materials that God and your local drugstore have provided.

Each element of the LCD for the digital pregnancy test is custom, just like an old Tamagotchi. That means one pin polarizes the layer with the test logo artwork on it. A second layer covers "`SEE LEAFLET`" for reporting error states, a third conveys "`NOT`" and a fourth, "`PREGNANT`." A given layer is active when the phase of the drive pin is 180 degrees out of phase with the COMMON pin.

So, let's go through the pins that make this happen.

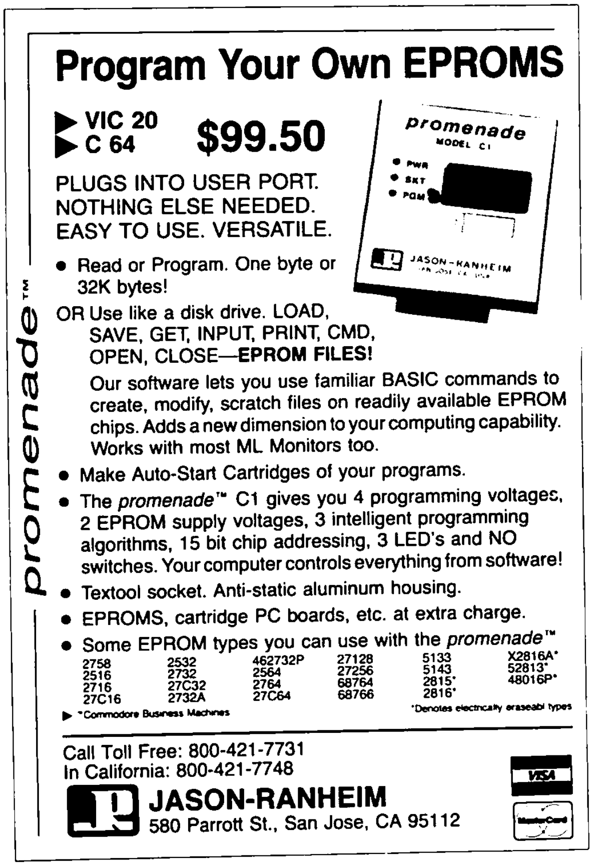
LCD Pin	Image
1	Common
2	"`NOT`"
3	"`PREGNANT`"
4	"`SEE LEAFLET`"
5	Logo



Pin 1 is the rightmost pin if you're looking at the LCD face and the pins are at the top of the package, opposite the reference designator. Make sure to not just short pins—you actually have to lift and move any pins you might be interested in swapping around. Cut a wire here, tack in a jumper there. Mix and match, and get ready to have a ball! Dance a jig! I mean, shoot, a fella could have a pretty good weekend in Vegas with all that.

At the time I was doing this work, the Holtek micro wasn't available for purchase from Digikey or Mouser, so in a fit of intellectual incuriosity, I didn't bother to crack it. Outcome: I can't give you any information on its internals other than what I've inferred from reverse-engineering the rest of the circuit. I'd love to see it done, though—just because the programming physical interface is obfuscated in the primary datasheet doesn't mean it's impossible. If I were doing this twice, I'd start with the ICE. The correct ICE tool for the job, assuming you're into that, is the CICE48U000006A. In the interest of speed, I based my redesign on a PIC16F1933 and a character LCD that fit nicely in the same window as the original.

The demo worked, but I never got paid. So, demo code and hardware design files are available for any neighbor who wants to buy me a beer.
Cheers!
–w0z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