„Listen to your heart“

Heart rate monitor implemented in GA144

Daniel Kalny
on behalf of GreenArrays

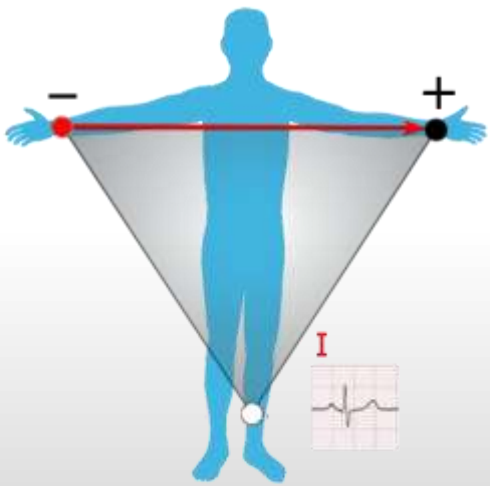
Forth Day 2018

heart rate monitors

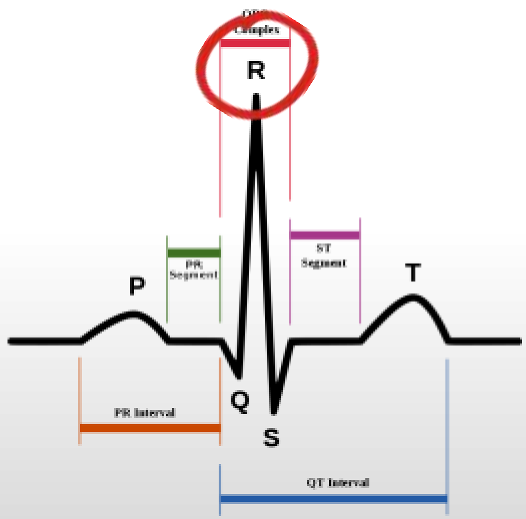
images: www.garmin.com, www.polar.com, www.amazon.com

electrocardiography

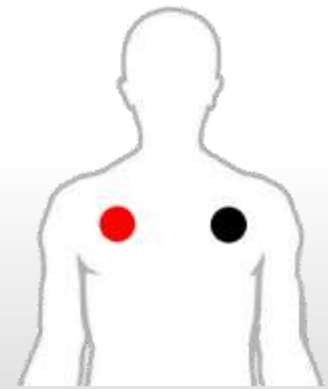
principles



three-electrode ECG



normal sinus rythm



two-electrode ECG
used in this application

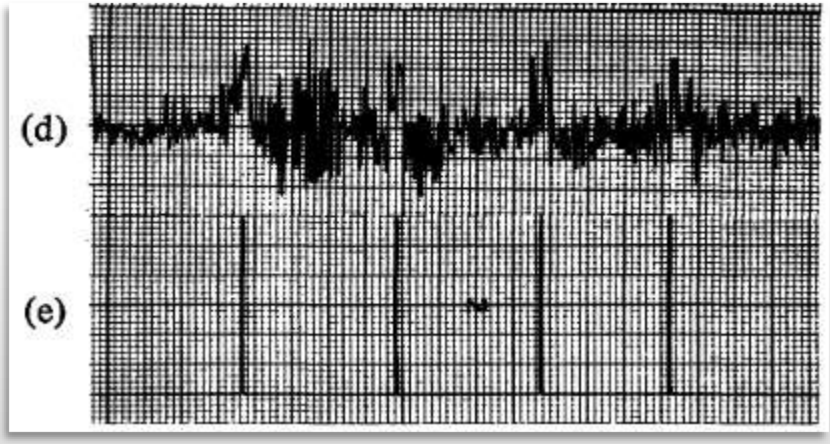
source: wikipedia

electrocardiography

signal processing

Pan and Tompkins algorithm [1]

- noise removal
- R-wave detection



Noisy ECG signal with R-waves located [1]

[1] J. Pan, W. J. Tompkins, IEEE Trans. Biomed. Eng., BME-32 (3) 1985 p. 203-6

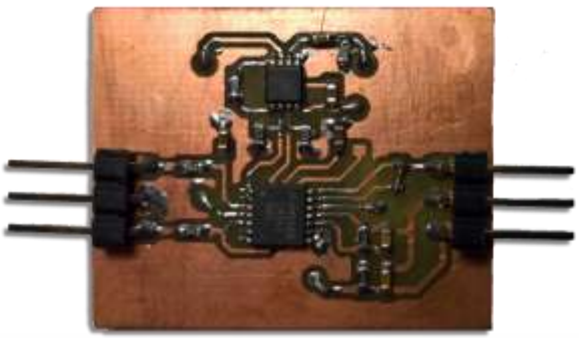
aims of this project

1) implement ECG signal acquisition in GA144
2) apply the Pan & Tompkins algorigthm for R-wave detection
3) determine energy consumed by the application

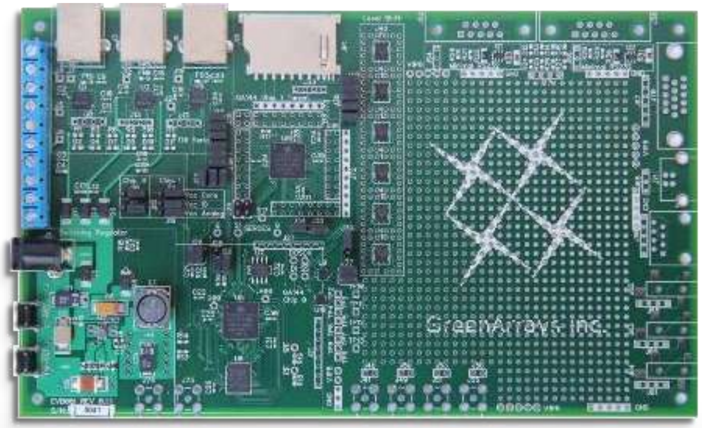
HARDWARE

setup

analog module



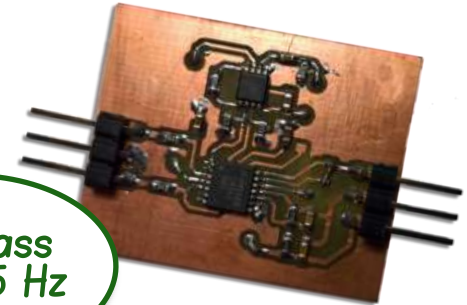
GA eval board

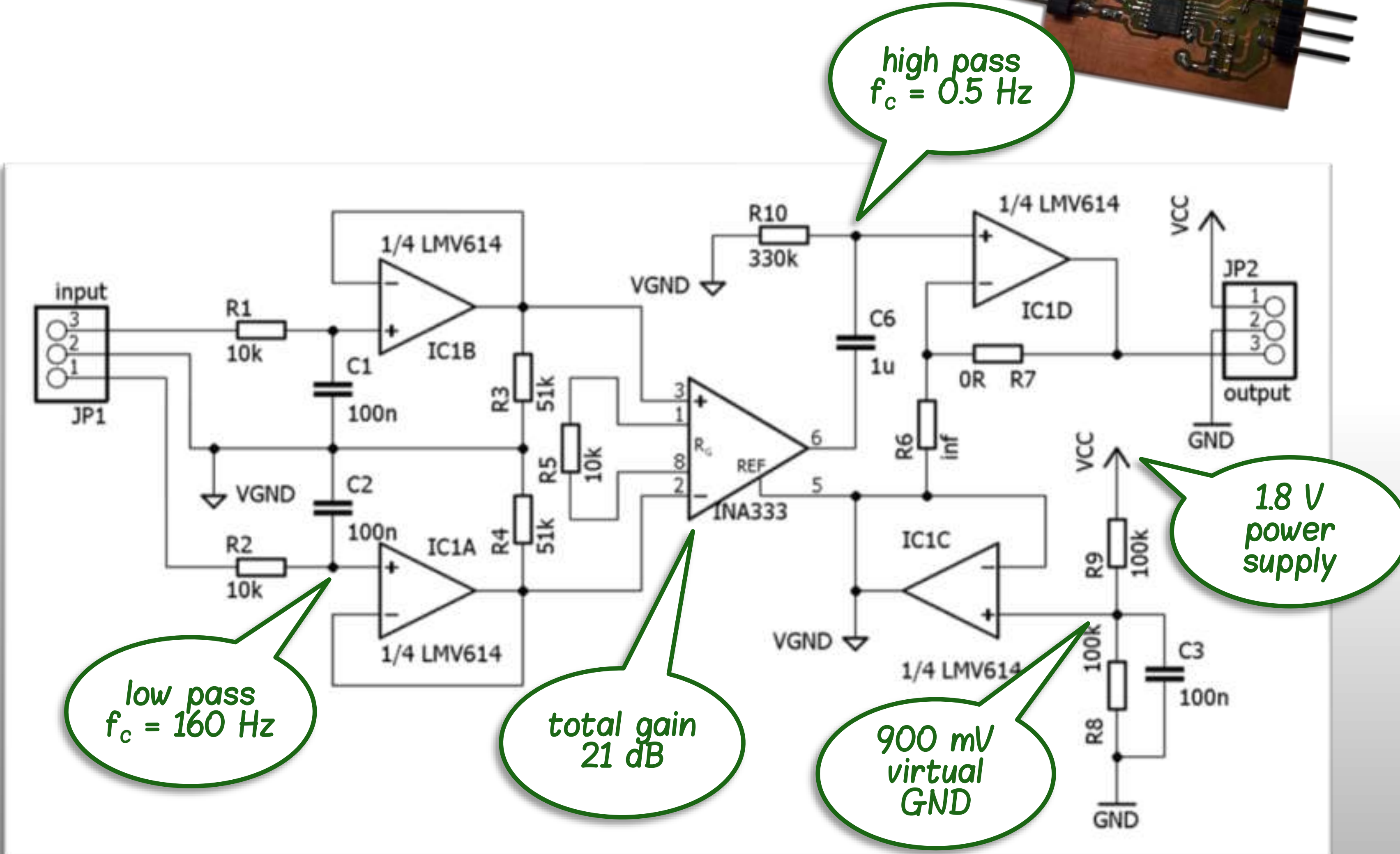


ECG electrodes

colorForth application

analog module



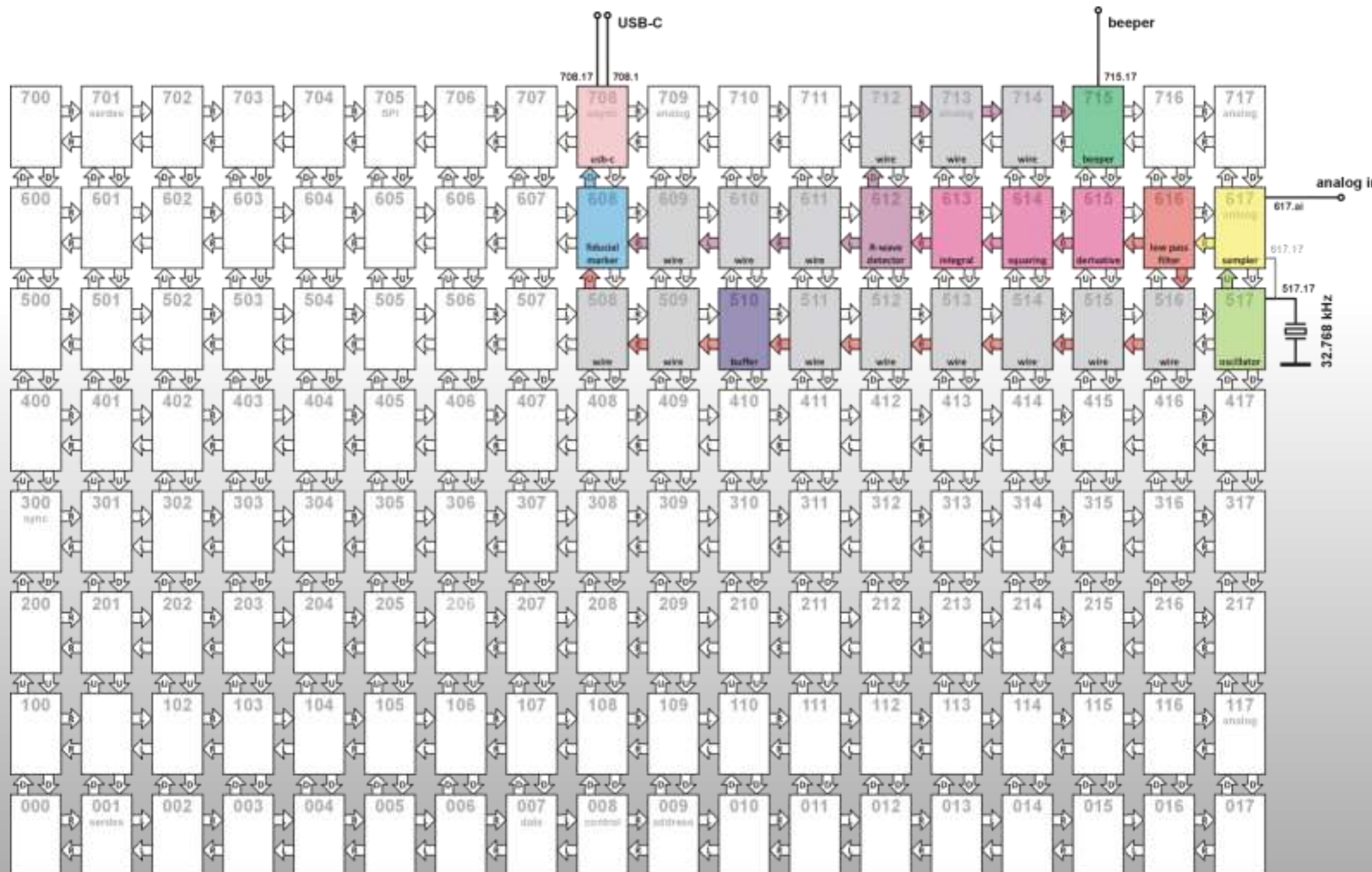


based on J. H. Yap *et al.*, Int. J. of Smart Home, 6 (4) 2012, p. 1–13

FLOORPLAN

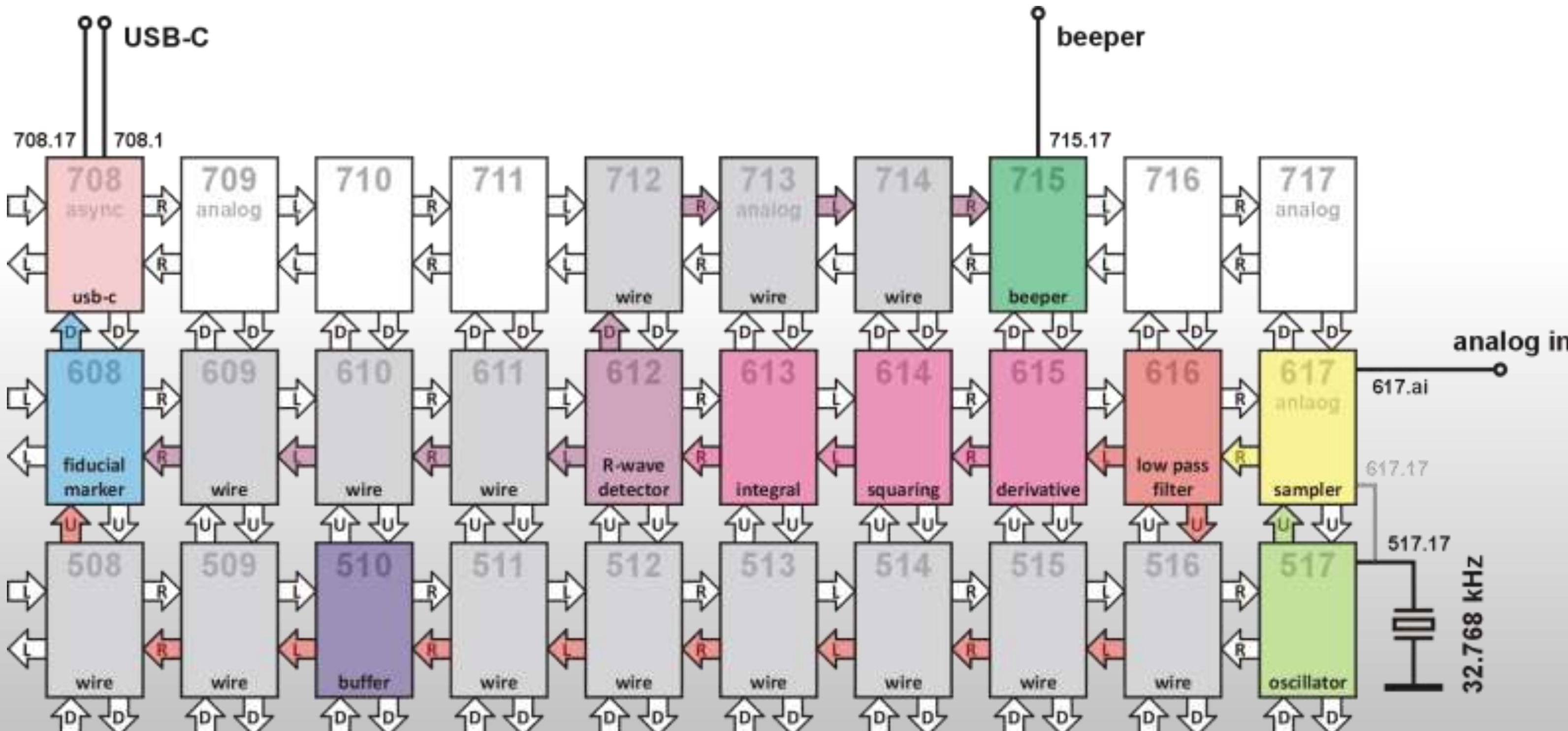
floorplan

target chip – 25 nodes



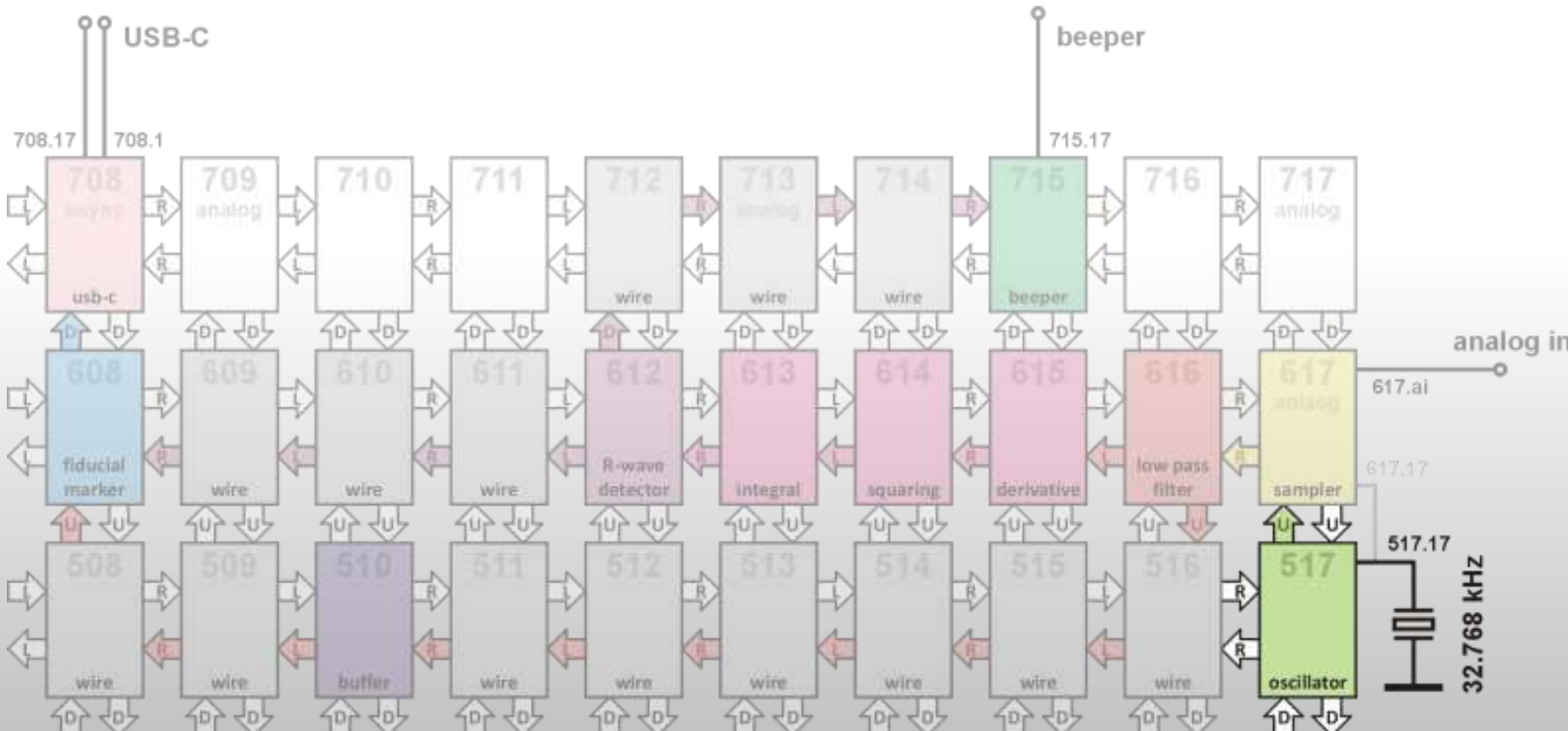
floorplan

application



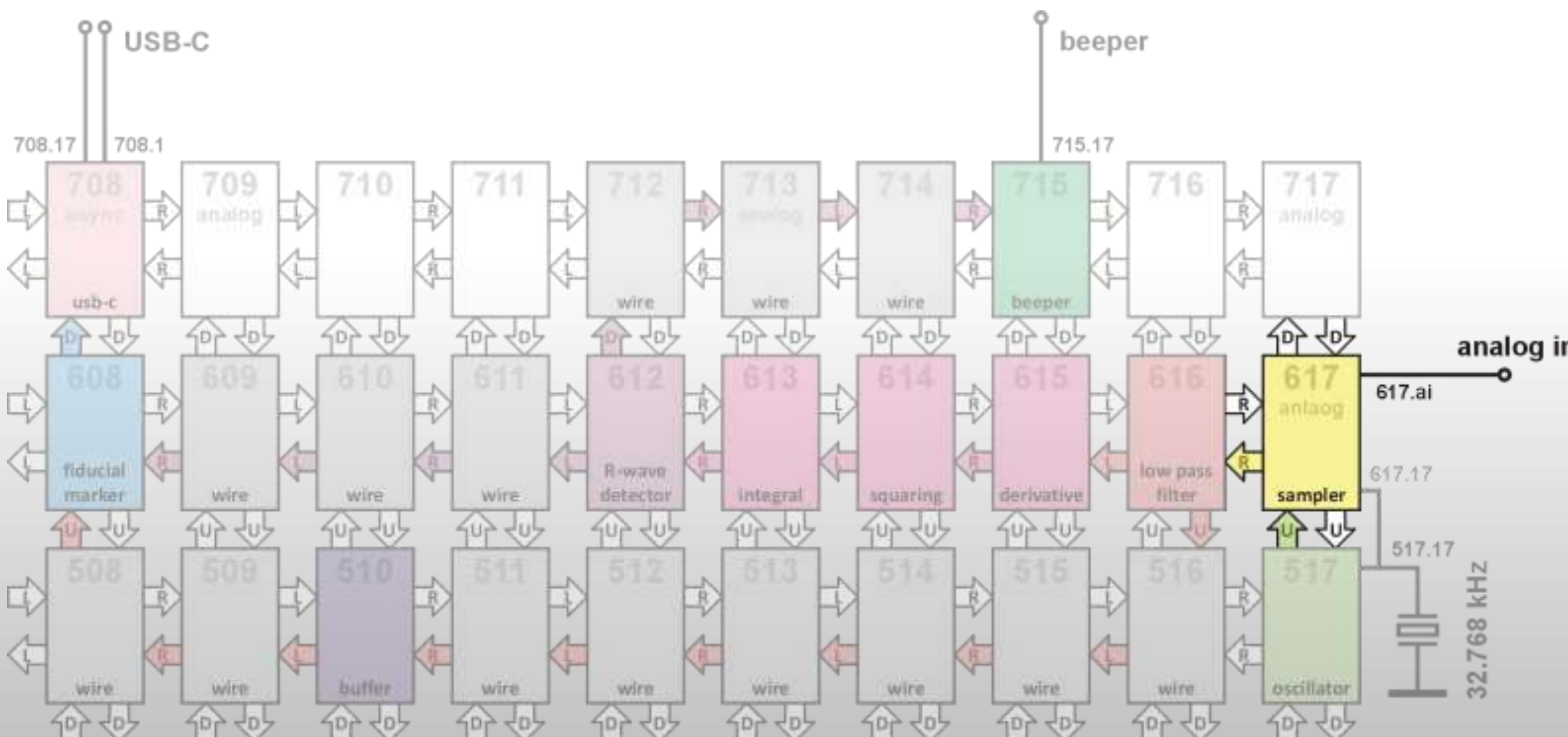
floorplan

oscillator



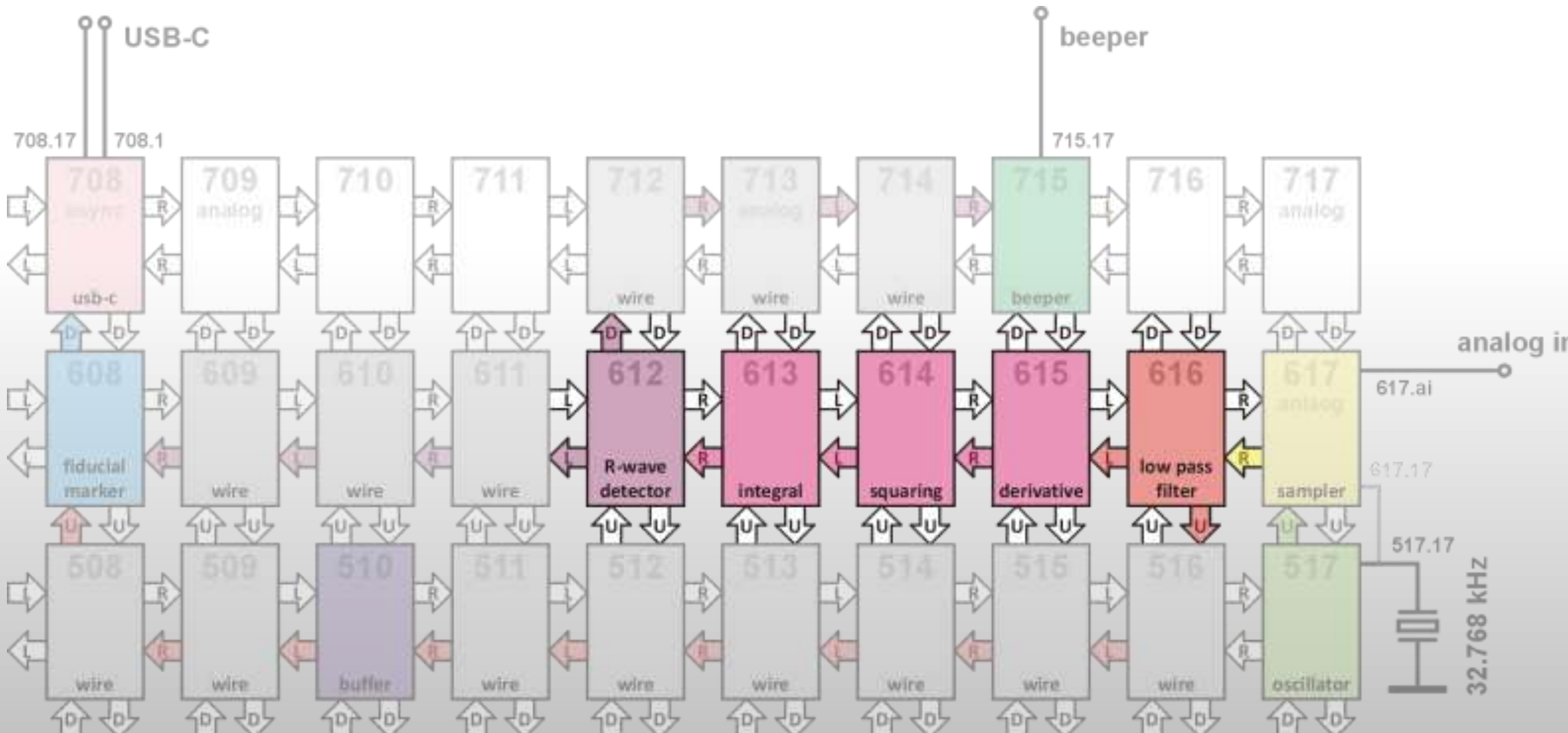
floorplan

sampler



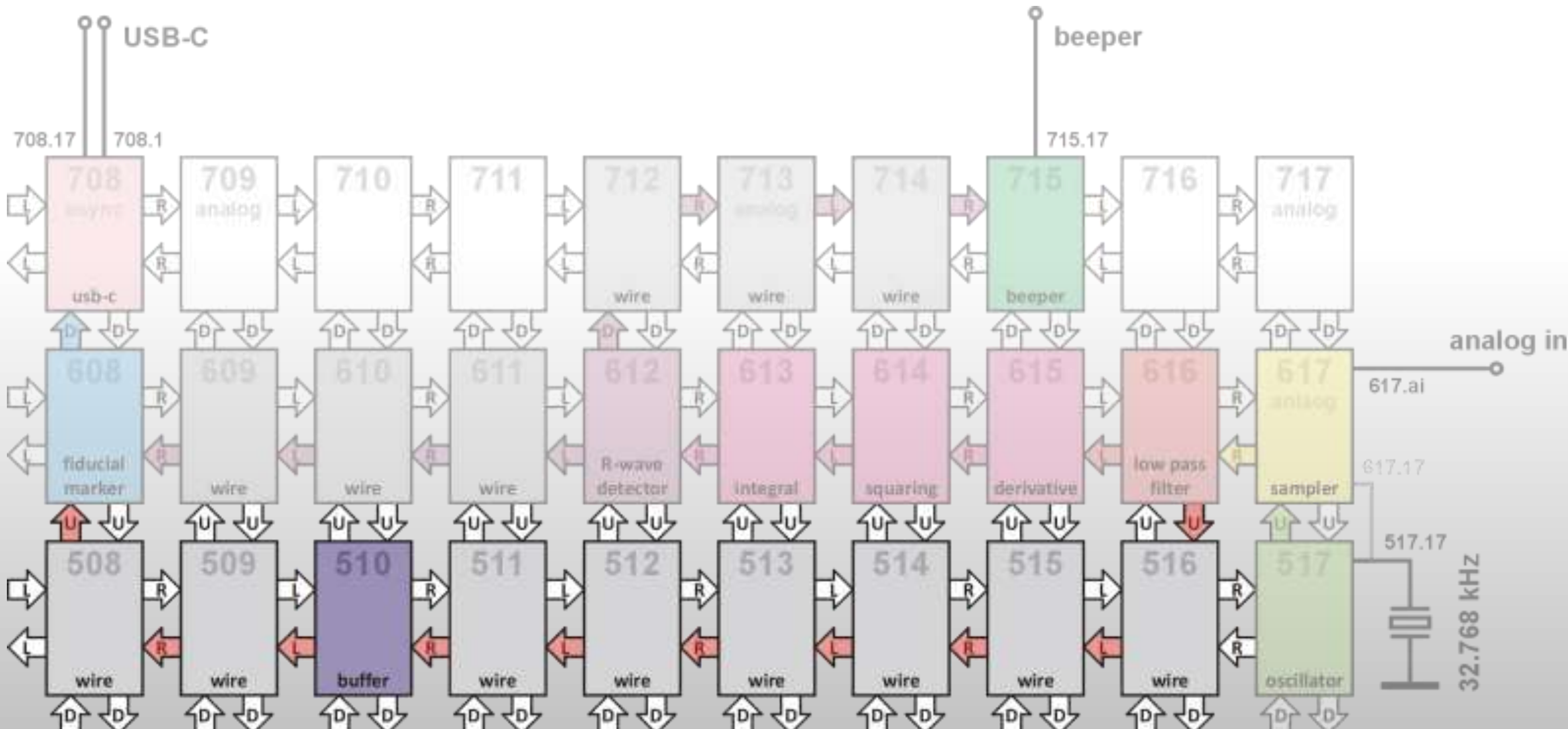
floorplan

signal processing



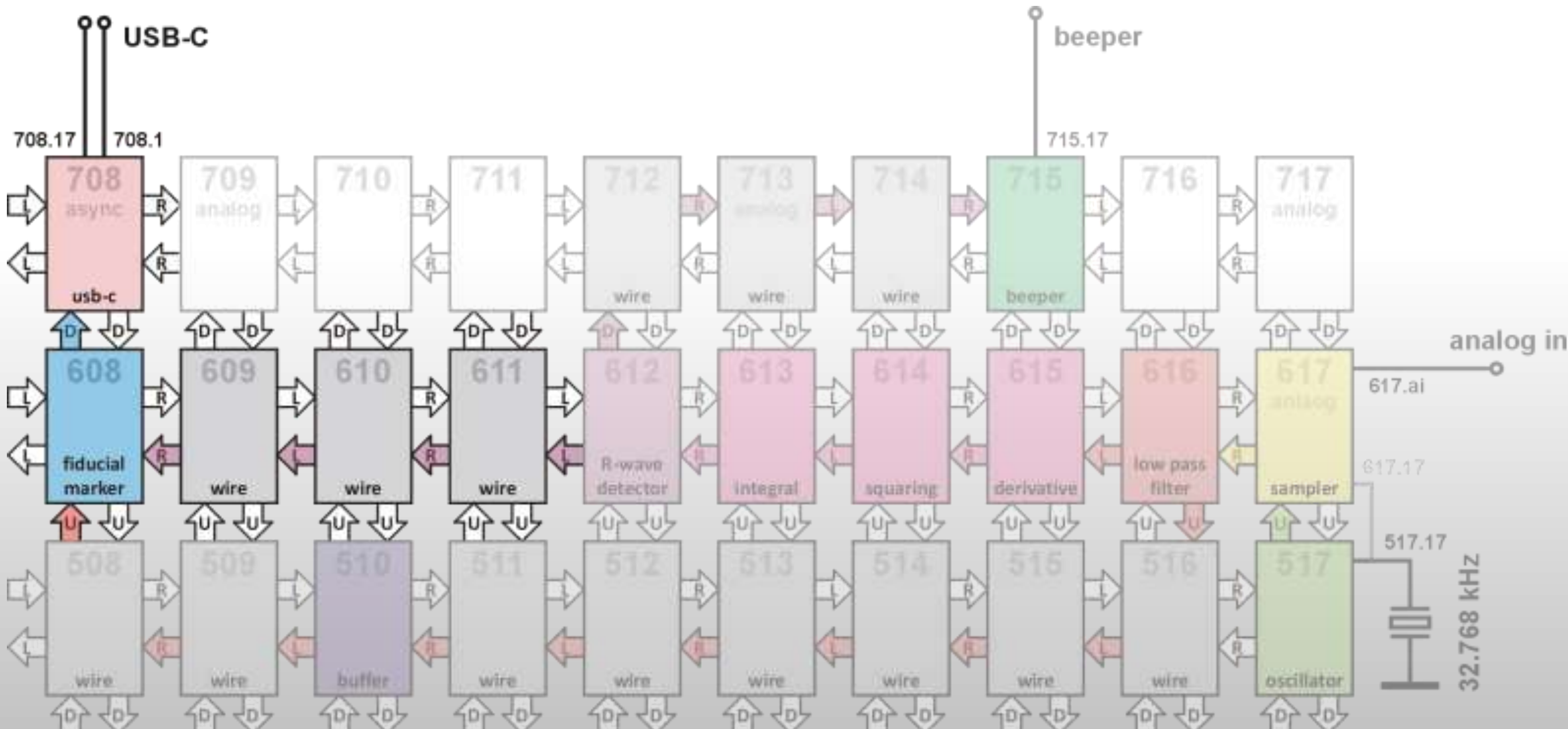
floorplan

ECG waveform path



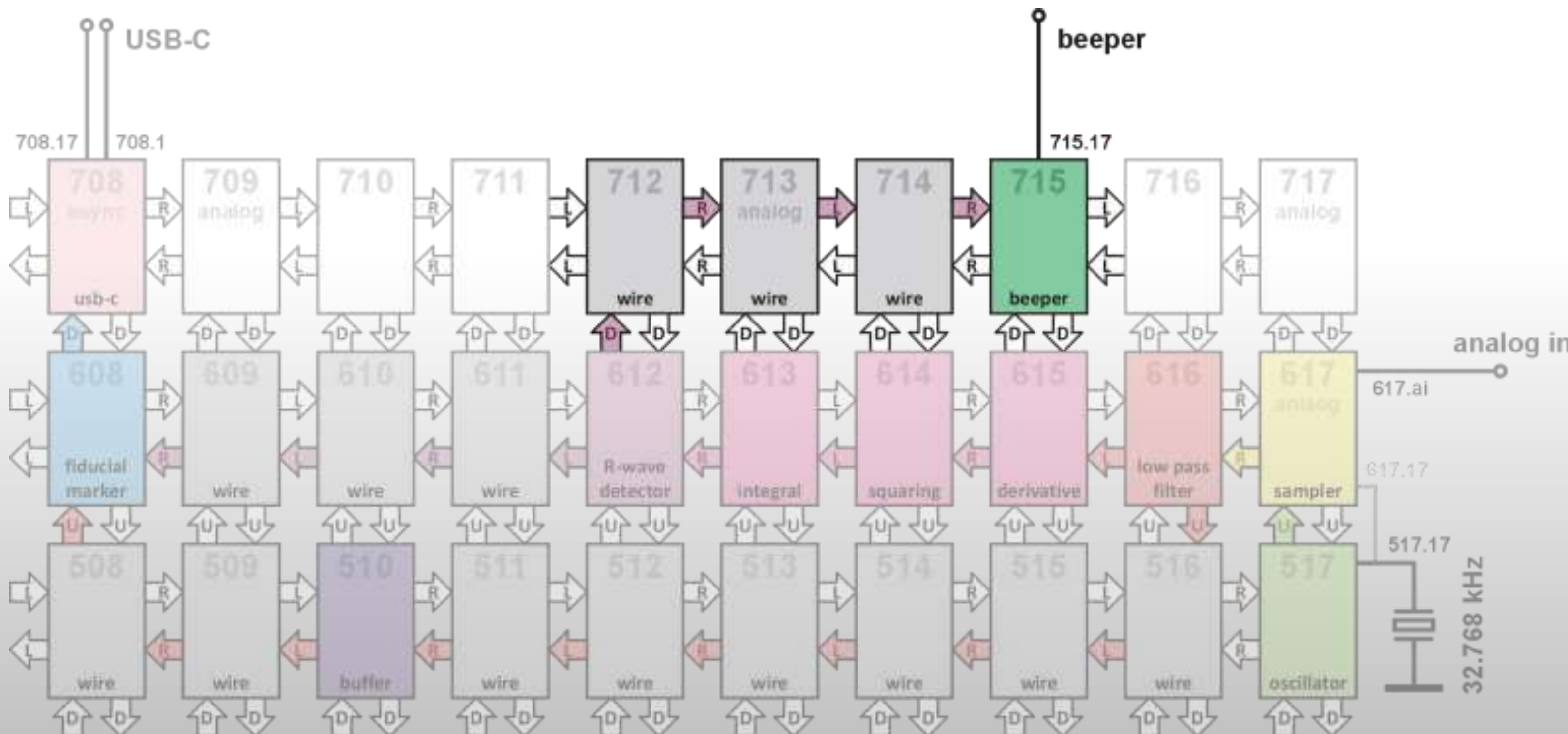
floorplan

ECG waveform to PC



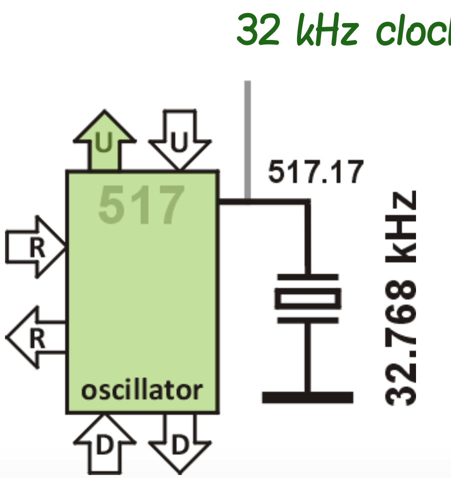
floorplan

acoustic signal



IMPLEMENTATION

oscillator



32.768 kHz quartz crystal

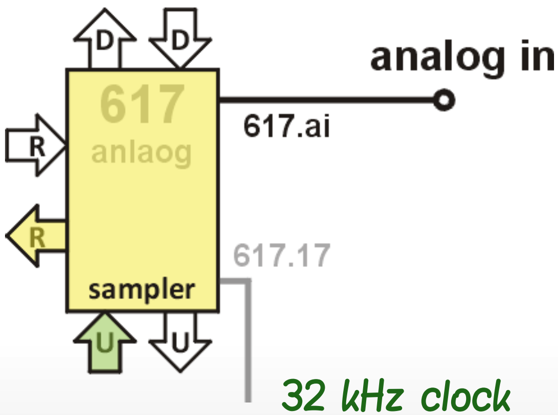
pin 17 shared with 617

```
880 list
32 khz xtal oscillator
517 +node 517 /ram up /a io /b 13 /p

reclaim 517 node 0 org
...
clang 14 12850 400 for dup 5000 -osc while
  drop 1 . + next dup or ! go ; then drop !
...
```

based on GreenArrays AN012

sampler

VCO from 5.6 GHz (V_{SS}) to 3.6 GHz (V_{DD})
linear between 750 and 1300 mV



thephysiologist.org

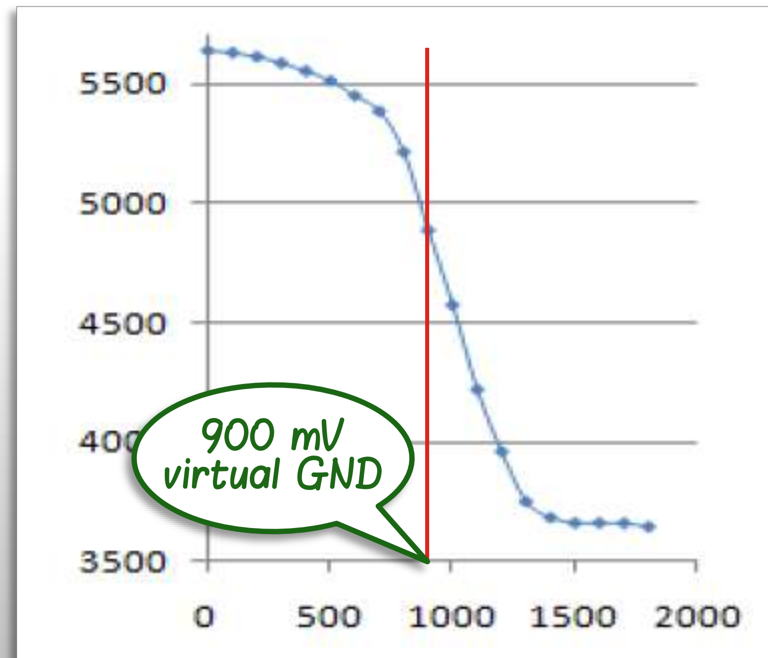
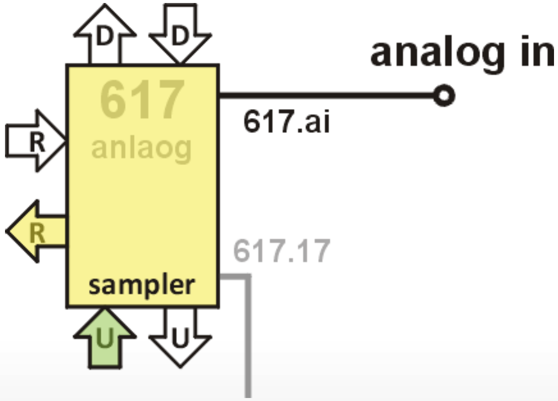


Figure 13 Typical ADC Transfer Function

DB001 F18A Technology Reference

sampler



write to LEFT to stop VCO

- suspended according to WD level

read first count form LEFT

- VCO starts running

wait – voltage sampling interval

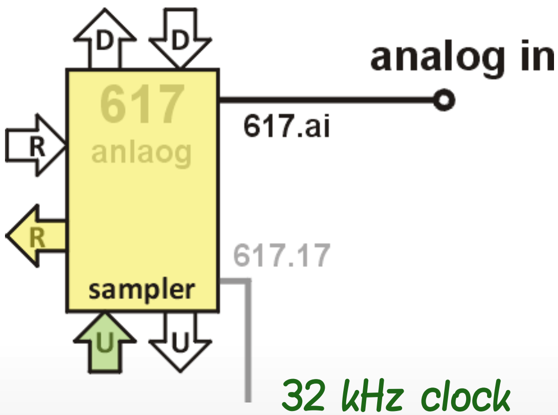
write to LDATA to stop VCO

- F18 not suspended

read second count from LDATA

count difference proportional to voltage

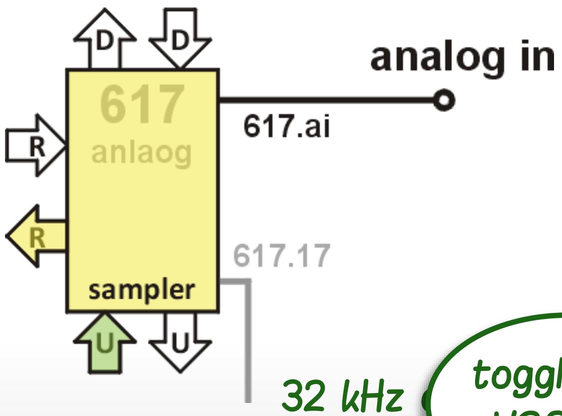
sampler



rising and falling clock edge
65,536 clock edges / second
256 samples / second

```
617 +node 617 /ram up /a io /b 1D go /p
  15555 15D55 15555 15D55 15555 15D55
  15555 15D55 15555 15D55 10 /stack

reclaim 617 node 0 org
1+ 1 . + ;
dif ab-d - . + -if - ; then 1+ ;
send n right b! !b io b! ;
adc -n 4000 or !b ldata a!
  dup ! @ 499 for unext dup ! @ dif ;
smpl left a! 254 for !b dup ! next
  !b ! adc send smpl ;
go 1D @ if drop smpl ; then drop go ;
```

sampler



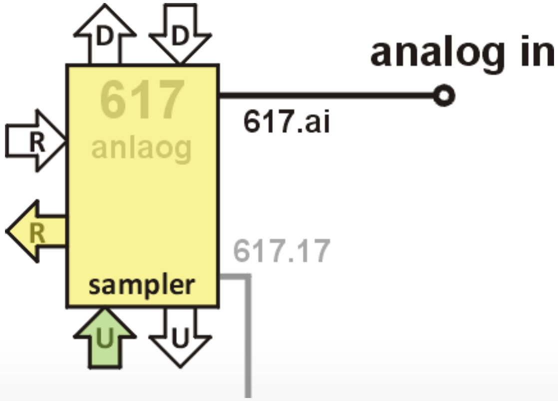
rising and falling clock edge

65,536 clock edges / second

256 samples / second

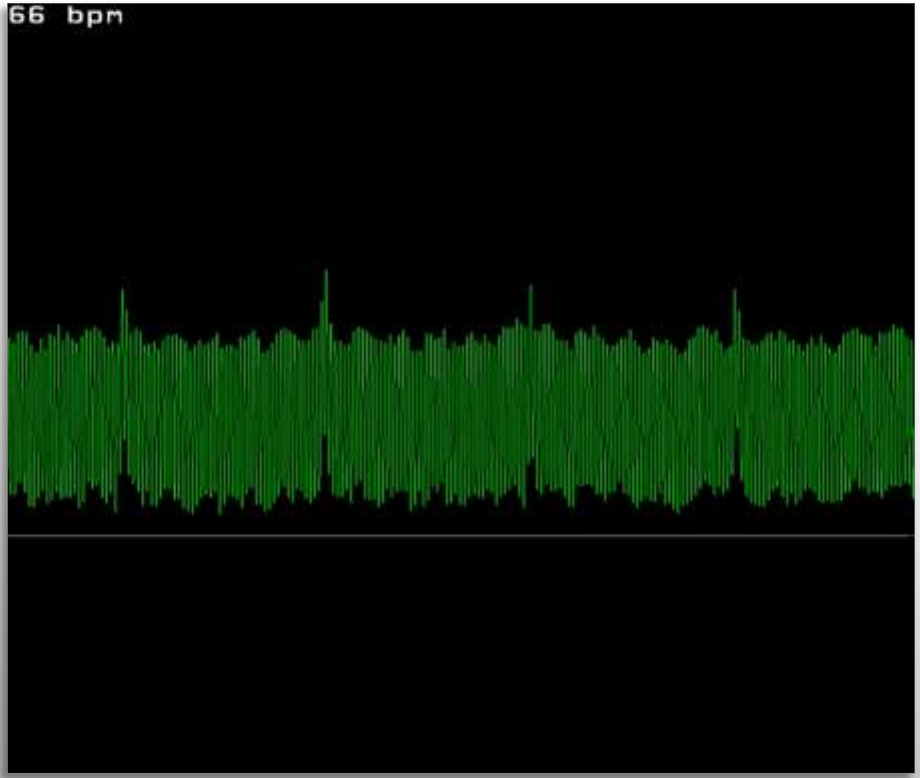
```
617 +node 617 /ram up /a io /b 1D go /p
  15555 15D55 15555 15D55 15555 15D55
  15555 15D55 15555 15D55 10 /stack

recl... 617 node 0 org
1
di...         . + ...       then 1+ ;
send n ...ght b...          ! ;
adc -n 4000 o... ...ta a!
  dup ! @ 499 for unext dup ! @ dif ;
smpl left a! 254 for !b dup ! next
  !b ! adc send smpl ;
   ... @ if drop smpl ; then drop go ;
```

sampler



strong 50 Hz noise

zero line offset



sampler output

signal processing

Pan & Tompkins algorithm [1]

band pass filter (5 – 15 Hz)

derivative

squaring

moving window integration

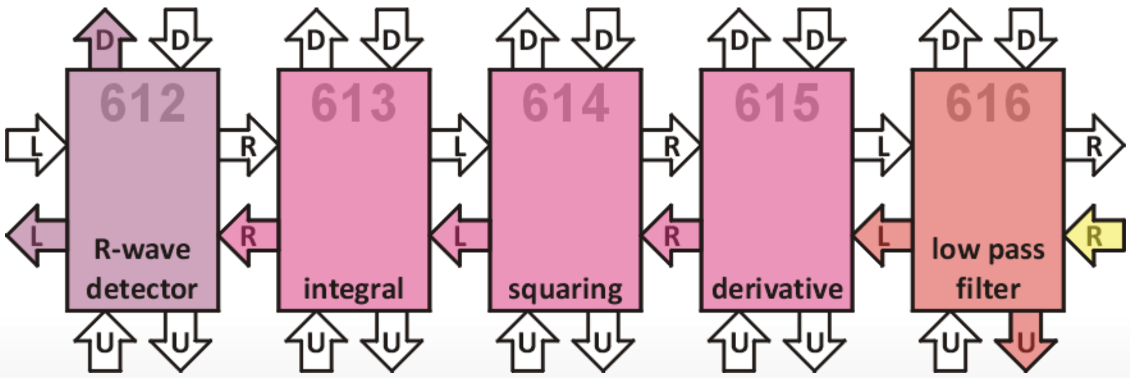
maximal slope detection

dynamic thresholds (not implemented)

[1] J. Pan, W. J. Tompkins, IEEE Trans. Biomed. Eng., BME-32 (3) 1985 p. 203-6

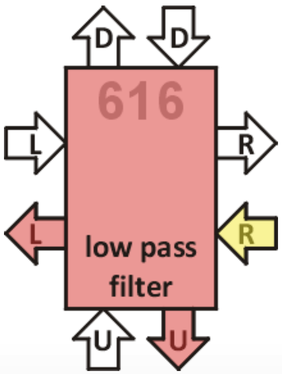
signal processing

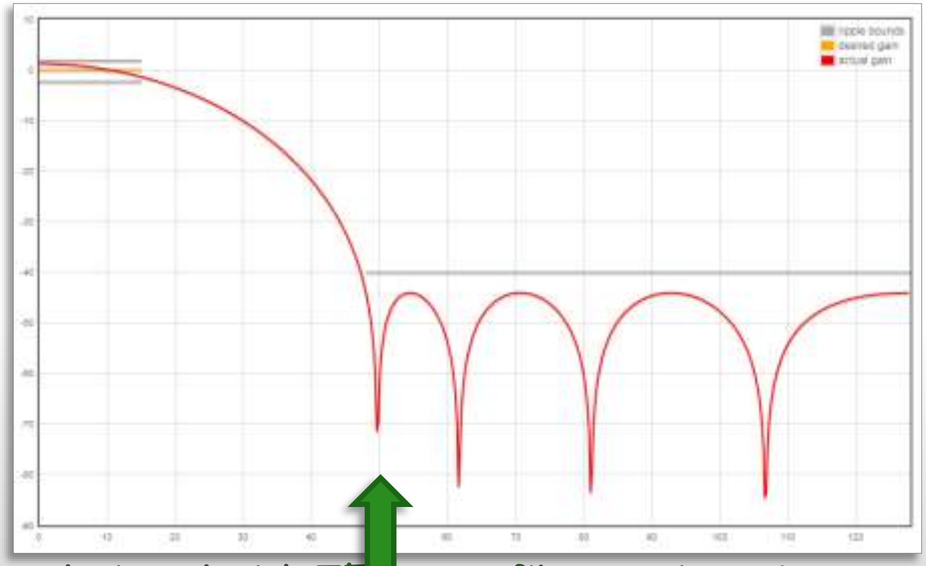
GA144 implementation



signal processing

low pass filter





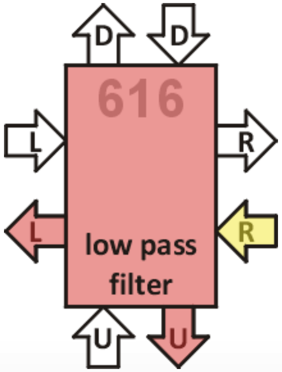
designed with TFilter, t-filter.engineerjs.com

implemented as FIR

passband	0 – 15 Hz	2.6 dB	ripple
stopband	48 – 128 Hz	-44 dB	attn.
notch	50 Hz	-70 dB	attn.

signal processing

low pass filter

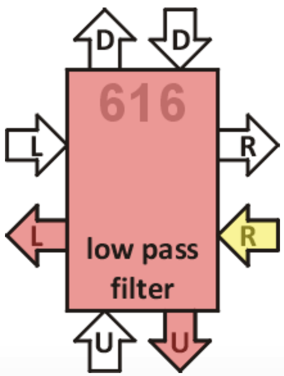


11 taps FIR filter

```
616 +node 616 /ram right /b 30 go /p

reclaim 616 node 0 org
lpf 10 taps
1333 , 0 , 5450 , 0 , 11377 , 0 ,
18824 , 0 , 24701 , 0 , 27096 , 0 ,
24701 , 0 , 18824 , 0 , 11377 , 0 ,
5450 , 0 , 1333 , 0 ,

30 org
go 30 dup or @b lpf drop 165 --lu a! ! go ;
```

signal processing

low pass filter



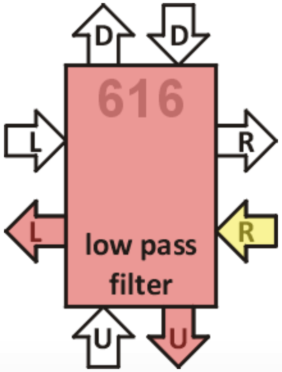
11 taps FIR filter

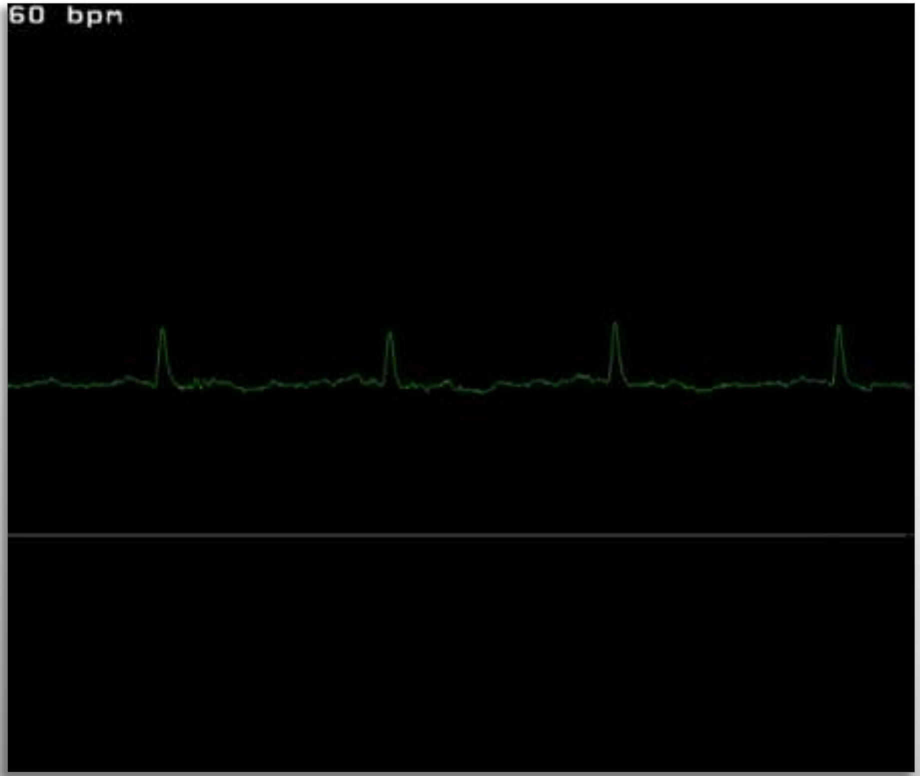
GA144 ROM

```
616 +node 6 ght /b 30 go /p

reclaim 616 node 0 org
lpf 10 taps
1333 , 0 , 5450 , 0 , 11377 , 0 ,
18824 , 0 , 24701 , 0 , 27096 , 0 ,
24701 , 0 , 18824 , 0 , 11377 , 0 ,
5450 , 0 , 1333 , 0 ,

30 org
go 30 dup or @b lpf drop 165 --lu a! ! go ;
```

signal processing

low pass filter

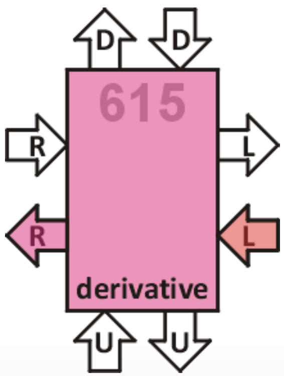




filter output

signal processing

differentiator



Pan & Tompkins

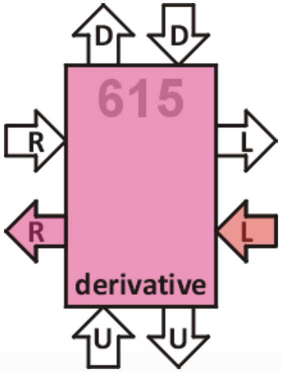
```
615 +node 615 /ram left /b 38 go /p

reclaim 615 node 0 org
d/dt 4 taps
-32768 , 0 , -65536 , 0 , 0 , 0 ,
65536 , 0 , 32768 , 0 ,

38 org
go 38 dup or @b d/dt drop right a! ! go ;
```

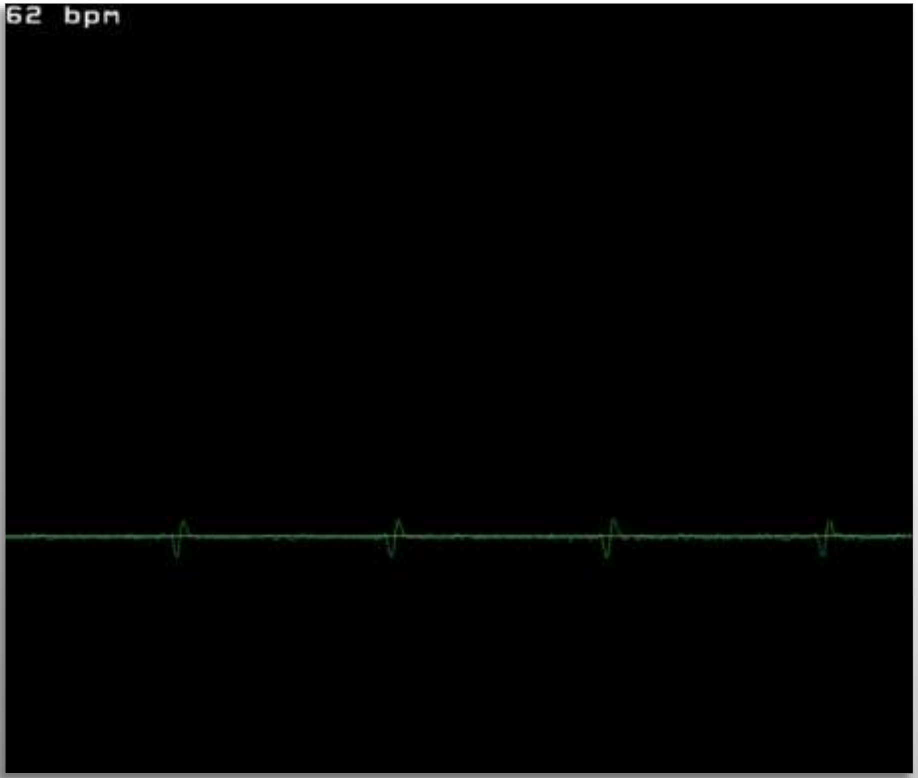
5-point stencil

x_{n-2} x_{n-1} x_n x_{n+1} x_{n+2}

signal processing

differentiator

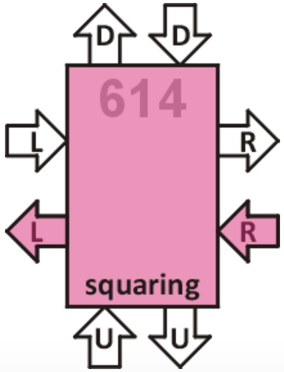




derivative output

signal processing

squaring function

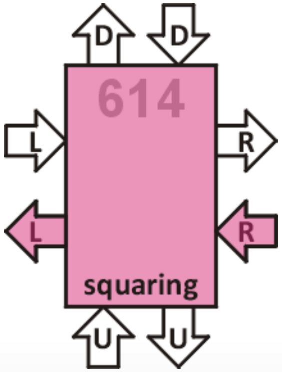


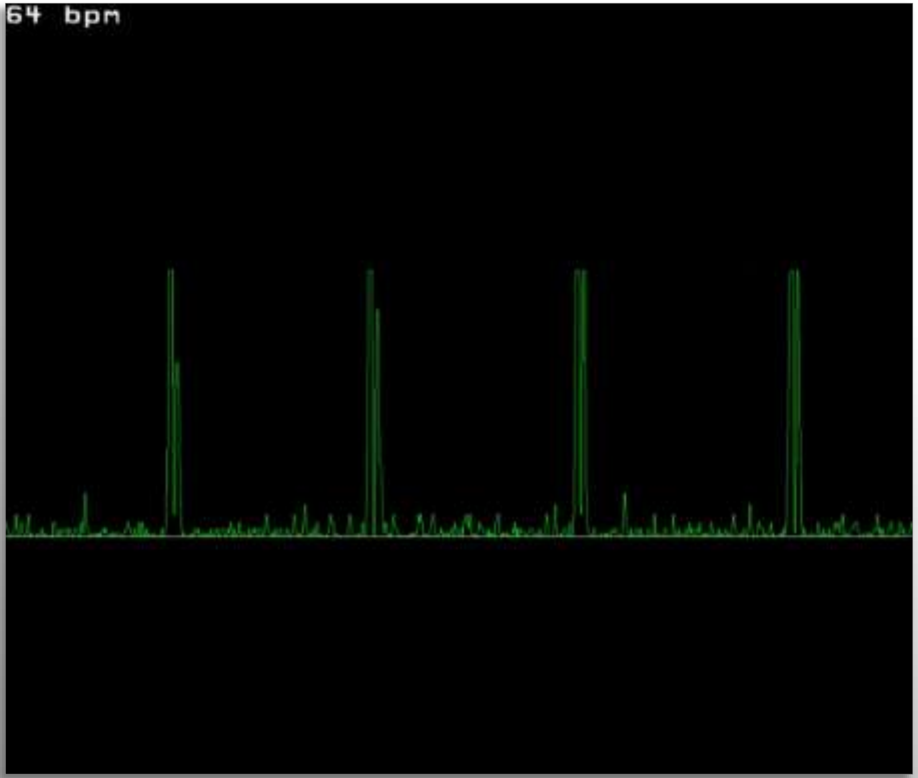
8-bit signed number

```
614 +node 614 /ram right /b 0 x2 /p

reclaim 614 node 0 org
x2 00 @b -if - 1 . + then
  dup 2* 2* 2* 2* 2* 2* 2* 2* over
  a! 0 7 for +* unext
  left a! ! x2 ;
```

signal processing

squaring function

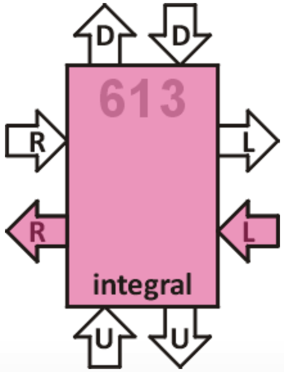




squaring function output

signal processing

moving window integration

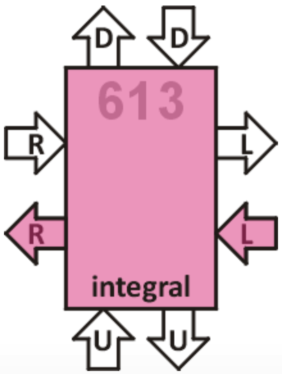


32-point window

```
613 +node 613 /ram 0 /a 1F5 r-l- /b
  0 1 /stack 20 sum /p

reclaim 613 node 0 org
0 , 0 , 0 , 0 , 0 , 0 , 0 , 0 ,
0 , 0 , 0 , 0 , 0 , 0 , 0 , 0 ,
0 , 0 , 0 , 0 , 0 , 0 , 0 , 0 ,
0 , 0 , 0 , 0 , 0 , 0 , 0 , 0 ,

20 org
sum s-s' 20 - @ . + -
  @b dup !+ . +
  a 1F and a!
  dup 2/ 2/ 2/ 2/ !b sum ;
```

signal processing

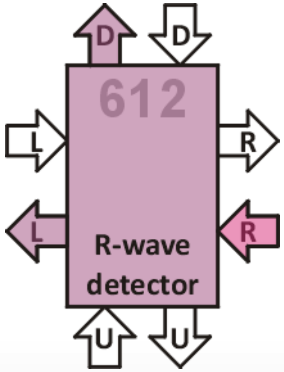
moving window integration



numerical integration output

signal processing

R-wave detection

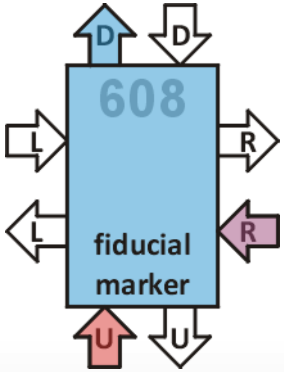


false flag on each point

true on rising edge only

```
612 +node 612 /ram right /a 135 -dl- /b
  0 0 2 /stack 15 go /p

reclaim 612 node 0 org
false dup dup or !b ;
step nx-n'd drop @ over - over . + ;
rise nx-n'x begin step 7 . + -
  -if false swap end then ;
fall nx-n'x begin step -7 . +
   -if false swap end then ;
true -1 !b ;
go 15 rise true fall false go ;
```

fiducial marker



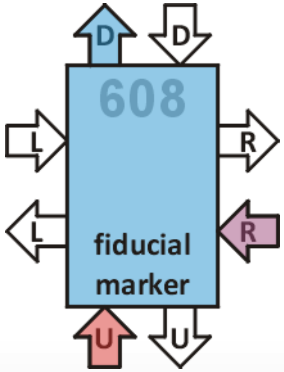
trim ECG signal

send fiducial marker and data to PC

```
608 +node 608 /ram 105 -d-u /a
 right /b A go /p

reclaim 608 node 0 org
min - over . + - -if + ; then drop ;
max - over . + - -if drop ; then + ;
go 0A @ 300 min -100 max @b ! ! go ;
```

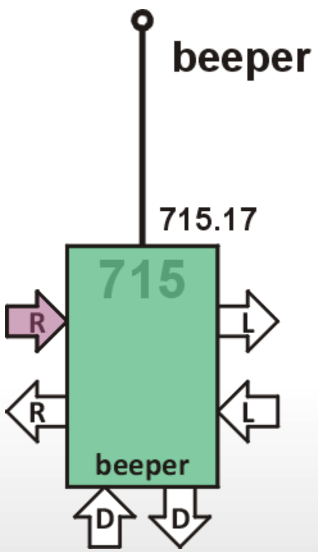
www.colorforth.com

fiducial marker



fiducial marker output

acoustic signal

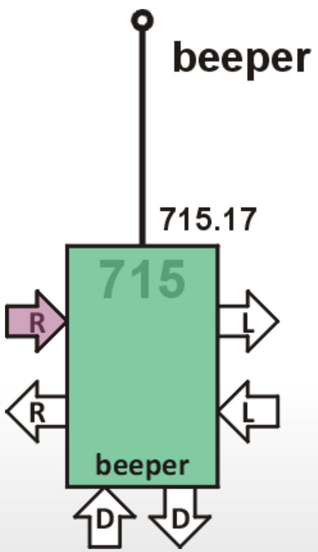


piezo buzzer

beep on true flag

```
715 +node 715 /ram right /a 12 go /p

reclaim 715 node 0 org
wait 00 22542 for . . . unext ;
click 04 30000 !b wait 20000 !b wait ;
beep 09 100 for click next
 1000 for wait next ;
go 12 @ if beep then go ; 15
```

acoustic signal



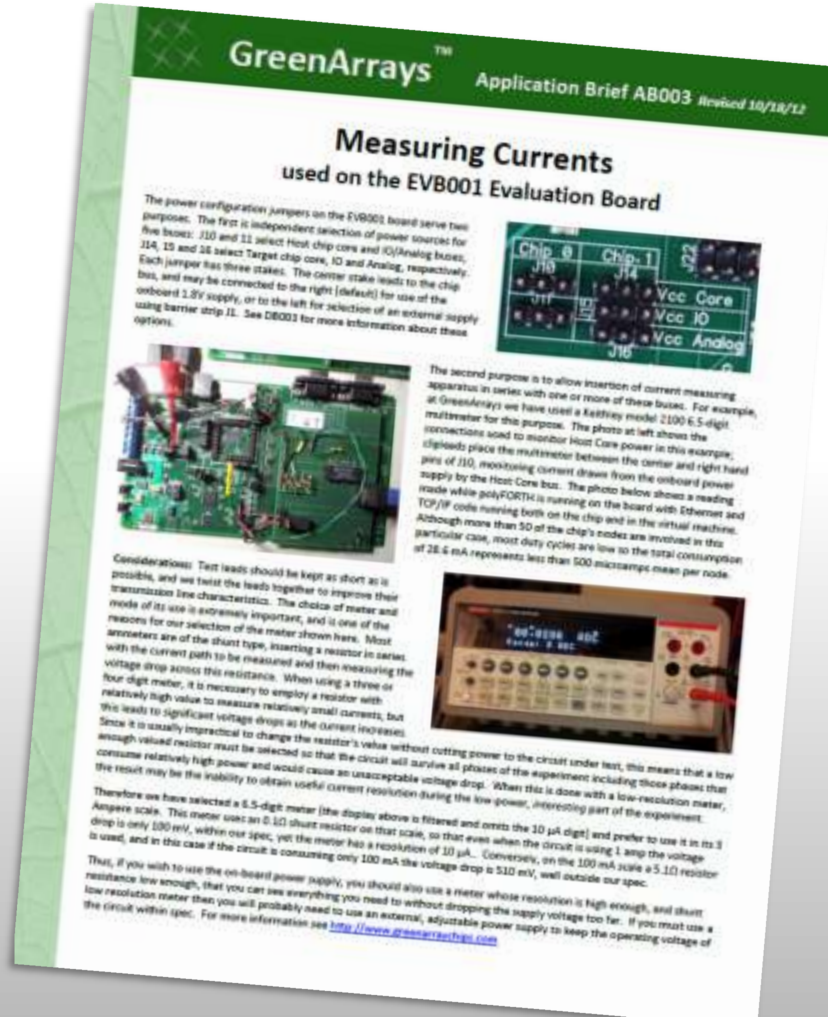
beeper output

ENERGY ASPECTS

current measurement

GA recommended [1,2]

on-board or external
  power source
6.5-digit meter
  low valued shunt resistor
  sufficient resolution
external shunt resistor


GreenArrays™ Application Brief AB003 Revised 10/18/12

Measuring Currents
used on the EVB001 Evaluation Board

The power configuration jumpers on the EVB001 board serve two purposes. The first is independent selection of power sources for five buses: J10 and 11 select Host chip core and IO/Analog buses, J14, 15 and 16 select Target chip core, IO and Analog, respectively. Each jumper has three stakes. The center stake leads to the chip bus, and may be connected to the right (default) for use of the onboard 1.8V supply, or to the left for selection of an external supply using barrier strip J1. See DB003 for more information about these options.

The second purpose is to allow insertion of current measuring apparatus in series with one or more of these buses. For example, at GreenArrays we have used a Keithley model 2100 6.5-digit multimeter for this purpose. The photo at left shows the connections used to monitor Host Core power in this example; clipleads place the multimeter between the center and right hand pins of J10, monitoring current drawn from the onboard power supply by the Host Core bus. The photo below shows a reading made while polyFORTH is running on the board with Ethernet and TCP/IP code running both on the chip and in the virtual machine. Although more than 50 of the chip's nodes are involved in this particular case, most duty cycles are low so the total consumption of 28.6 mA represents less than 500 microamps mean per node.

Considerations: Test leads should be kept as short as is possible, and we twist the leads together to improve their transmission line characteristics. The choice of meter and mode of its use is extremely important, and is one of the reasons for our selection of the meter shown here. Most ammeters are of the shunt type, inserting a resistor in series with the current path to be measured and then measuring the voltage drop across this resistance. When using a three or four digit meter, it is necessary to employ a resistor with relatively high value to measure relatively small currents, but this leads to significant voltage drops as the current increases. Since it is usually impractical to change the resistor's value without cutting power to the circuit under test, this means that a low enough valued resistor must be selected so that the circuit will survive all phases of the experiment including those phases that consume relatively high power and would cause an unacceptable voltage drop. When this is done with a low-resolution meter, the result may be the inability to obtain useful current resolution during the low power, *interesting* part of the experiment.

Therefore we have selected a 6.5-digit meter (the display above is filtered and omits the 10 µA digit) and prefer to use it in its 3 Ampere scale. This meter uses an 0.1Ω shunt resistor on that scale, so that even when the circuit is using 1 amp the voltage drop is only 100 mV, within our spec, yet the meter has a resolution of 10 µA. Conversely, on the 100 mA scale a 5.1Ω resistor is used, and in this case if the circuit is consuming only 100 mA the voltage drop is 510 mV, well outside our spec.

Thus, if you wish to use the on-board power supply, you should also use a meter whose resolution is high enough, and shunt resistance low enough, that you can see everything you need to without dropping the supply voltage too far. If you must use a low resolution meter then you will probably need to use an external, adjustable power supply to keep the operating voltage of the circuit within spec. For more information see http://www.greenarraychips.com

[1] GreenArrays AB003 Measuring Currents used on the EVB001 Evaluation Board
[2] GreenArrays AN012 Controlling the TI® SensorTag with the GA144

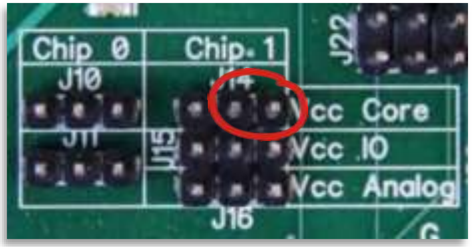
current measurement

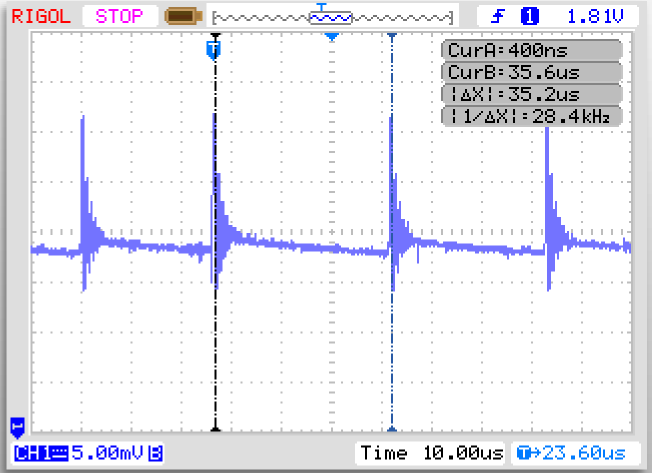
methodology 1

J14-2,3 on EVB (V_{cc} core)

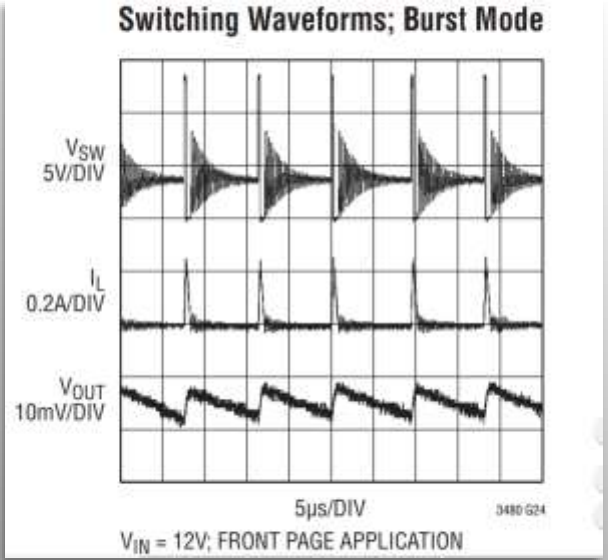
2.2 Ohm resistor 

scope probe on pinhead 2





scope trace



from LT3480 datasheet

current measurement

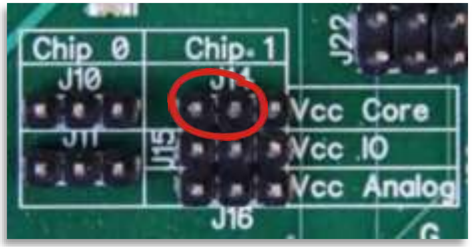
methodology 2

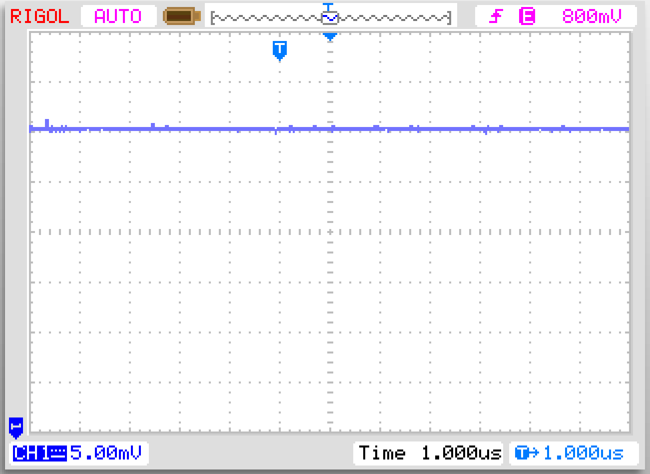
J14-1,2 on EVB (V_{cc} core)

2.2 Ohm resistor 

3V battery + 1.8V LDO (TLV70218)

scope probe on pinhead 2





scope trace

current measurement

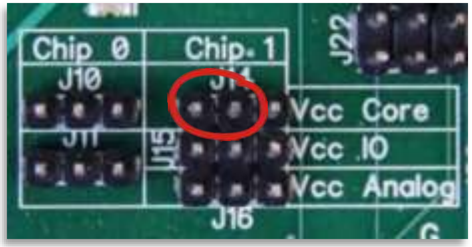
methodology 2

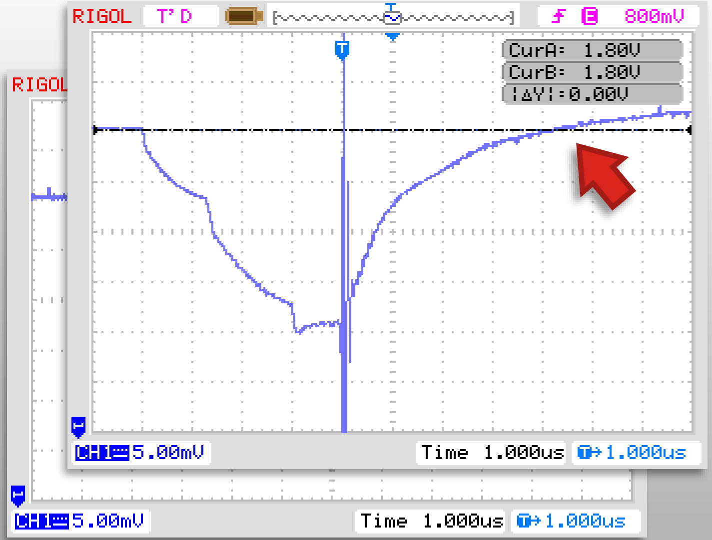
J14-1,2 on EVB (V_{cc} core)

2.2 Ohm resistor 

3V battery + 1.8V LDO (TLV70218)

scope probe on pinhead 2





scope trace

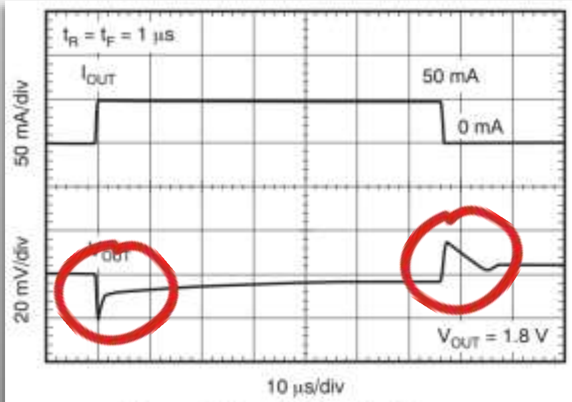


Figure 26. Load Transient Response

from TLV70218 datasheet

current measurement

methodology 2

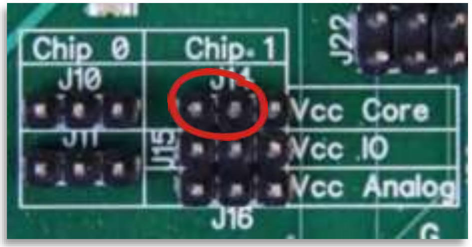
J14-1,2 on EVB (V_{cc} core)

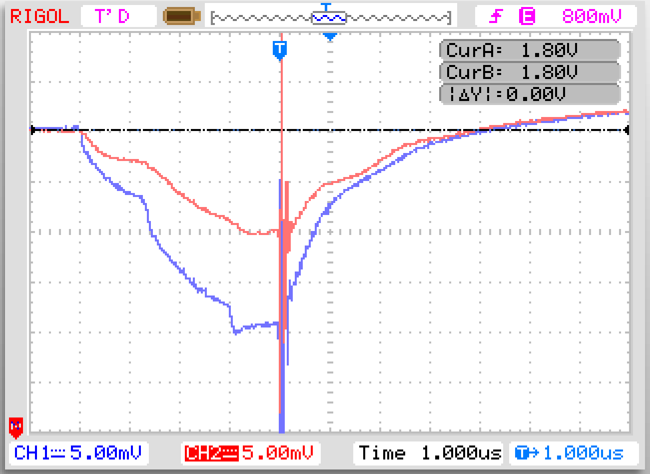
2.2 Ohm resistor 

3V battery + 1.8V LDO (TLV70218)

differential measurement

between pinheads 1 and 2





scope trace

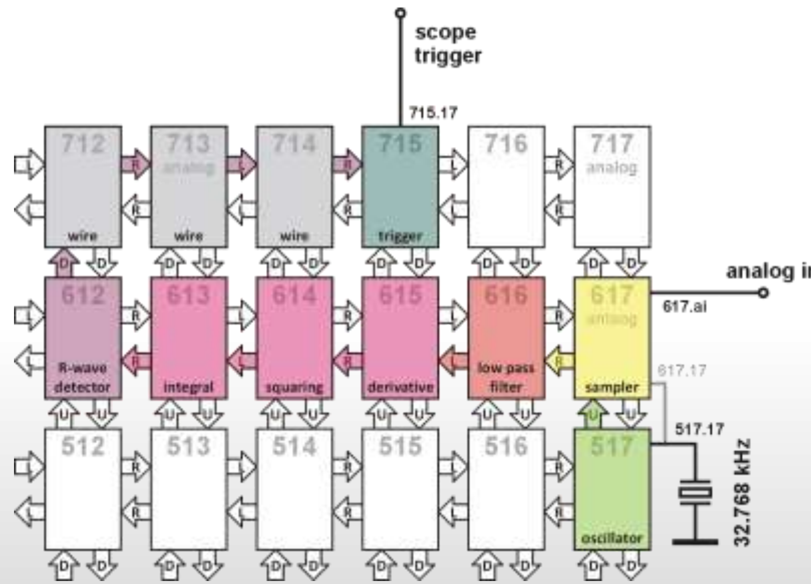
heart rate monitor

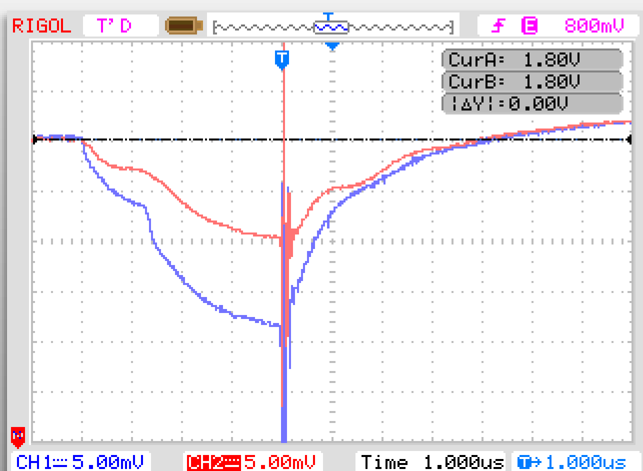
current vs time

no ECG waveform path

no data to PC

beeper node as scope trigger

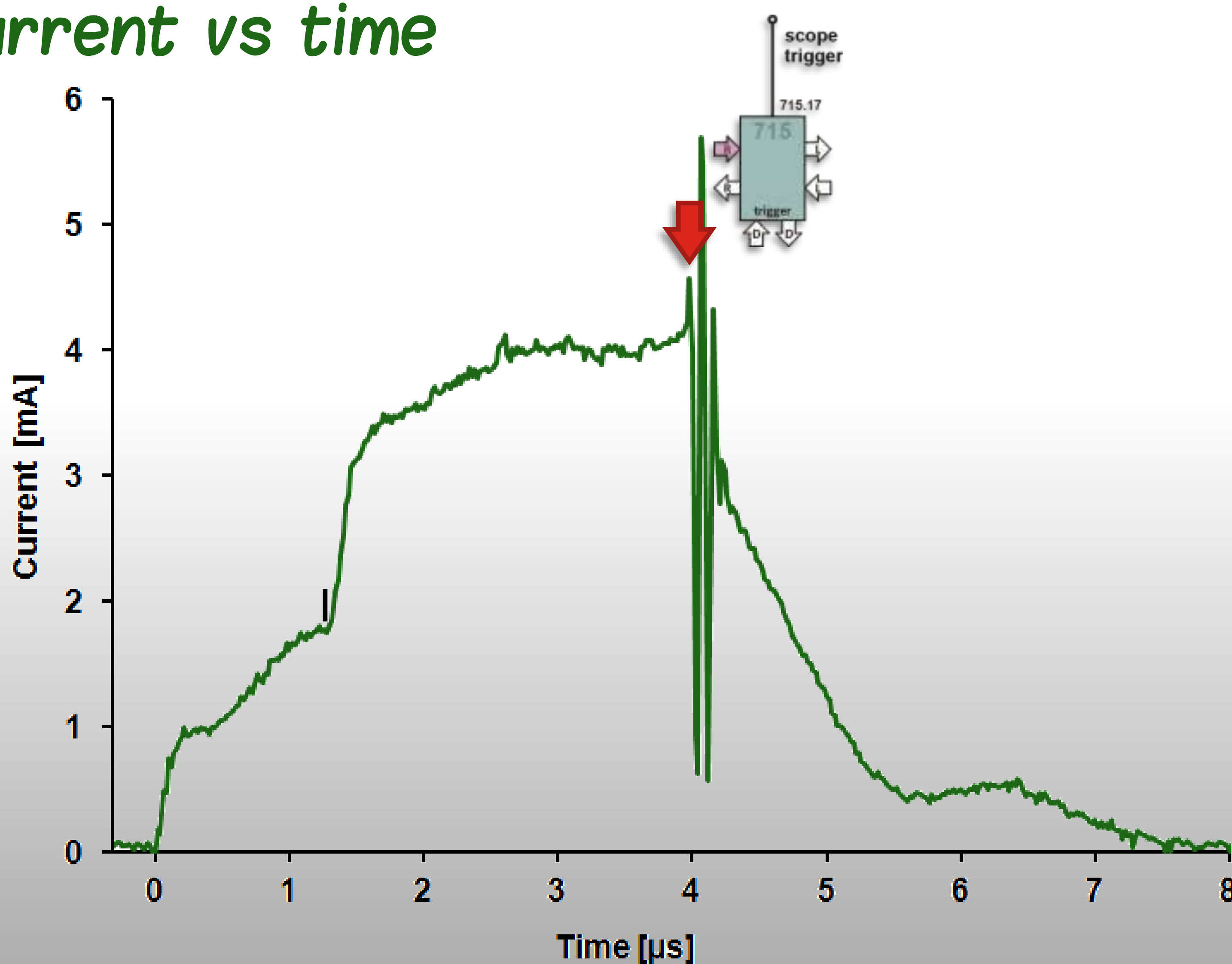




scope trace

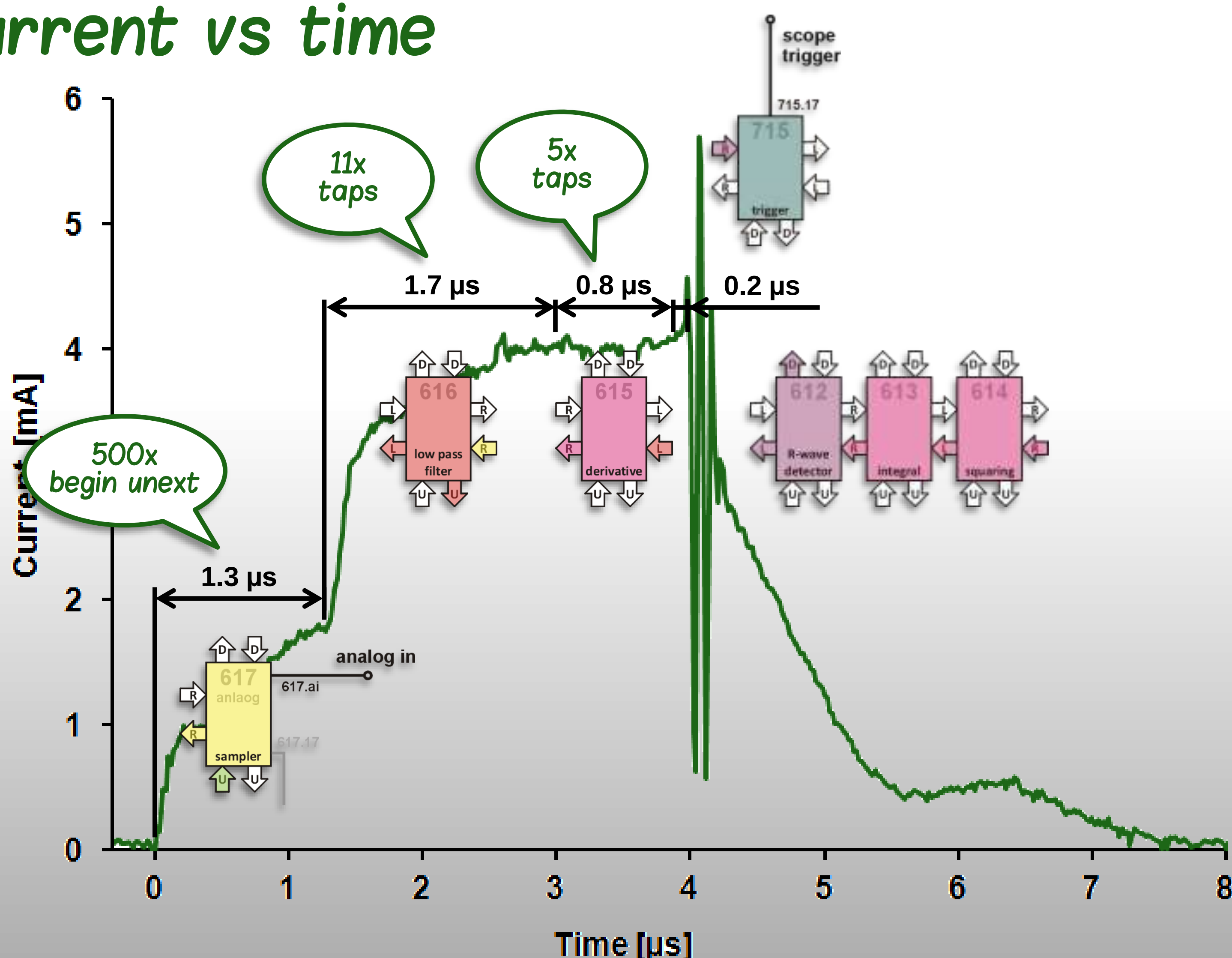
heart rate monitor

current vs time



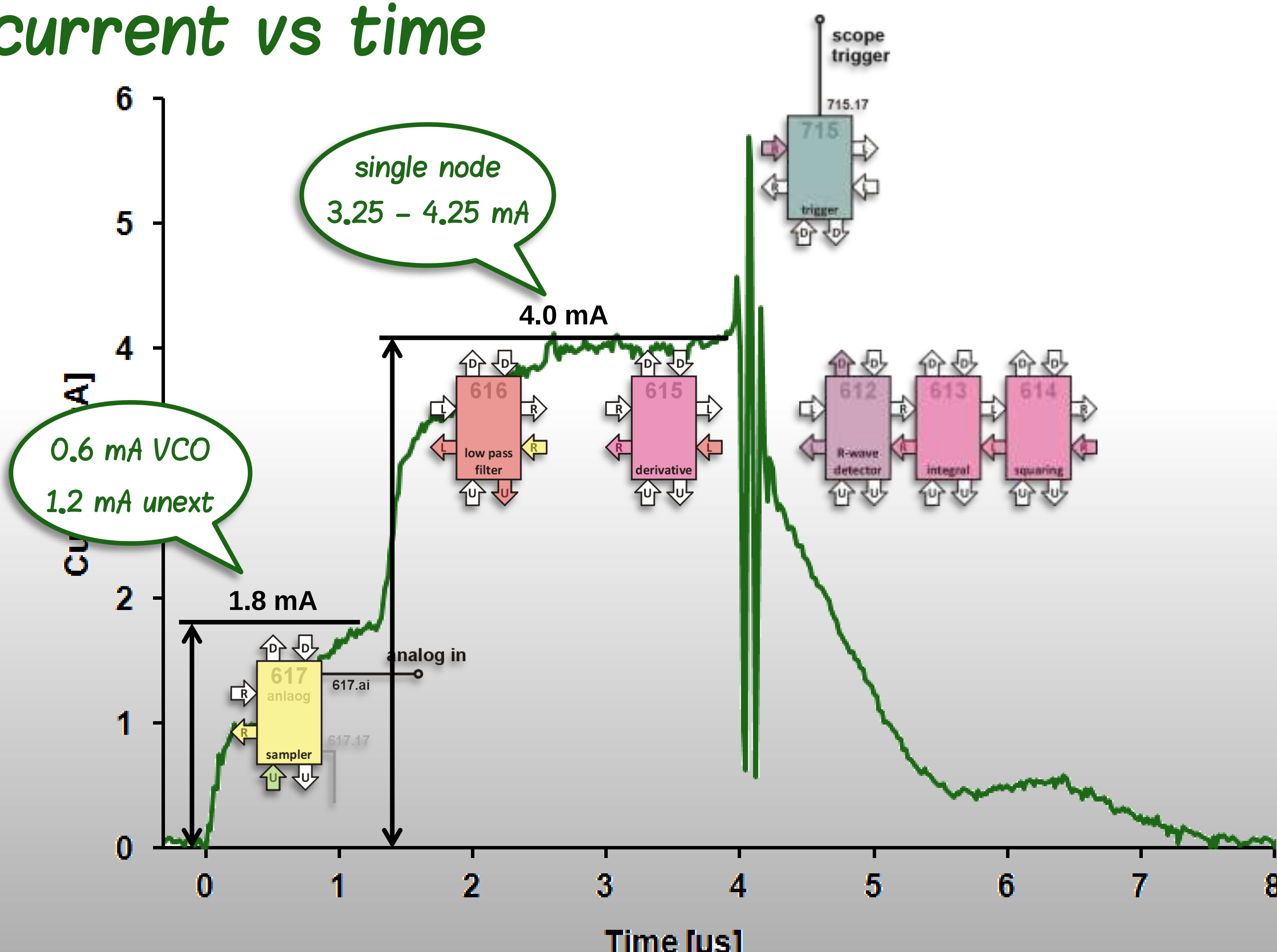
heart rate monitor

current vs time



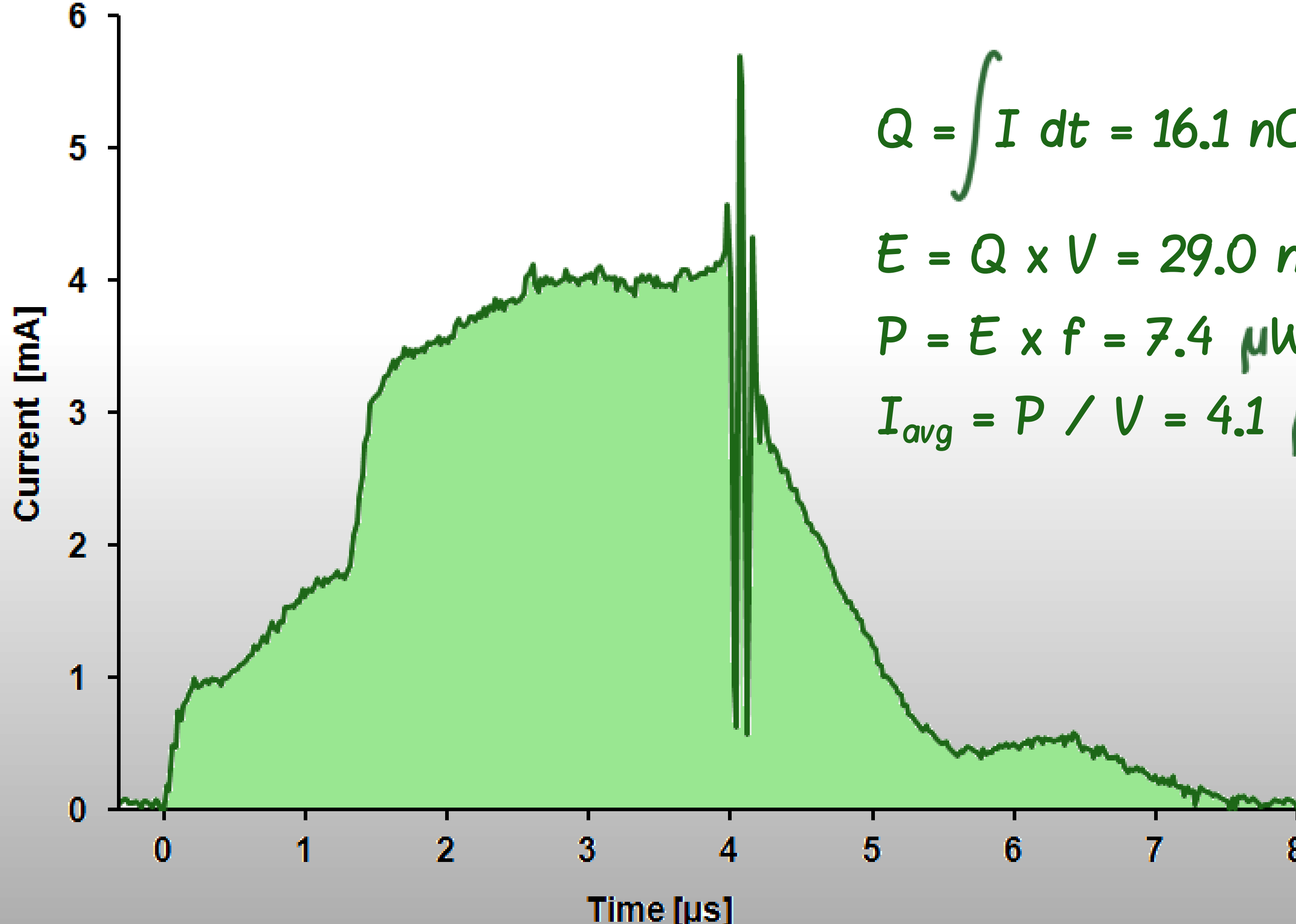
heart rate monitor

current vs time



heart rate monitor

energy and power



$Q = \int I\,dt = 16.1\ nC$

$E = Q \times V = 29.0\ nJ$

$P = E \times f = 7.4\ \mu W$

$I_{avg} = P / V = 4.1\ \mu A$

heart rate monitor

battery lifetime

CR2032: 235 mAh (@ 190 μA, to 2.0V) [1]

GA144 fully suspended: 7 μA [2]

HRM application: 4 μA

HRM running continuously:

2.4 years

[1] Energizer CR2032 datasheet
[2] GreenArrays DB002 G144A12

CONCLUSION

suggested extensions

- capacitive ECG electrodes
- wireless communication
  - ANT, Bluetooth LE
  - smart phone application
- energy harvester
  - vibrations
  - body heat

acknowledgements

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Chuck Moore

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