Using digital Phase-Locked Loop (PLL) technique for assessment of periodic body movement patterns on a mobile phone

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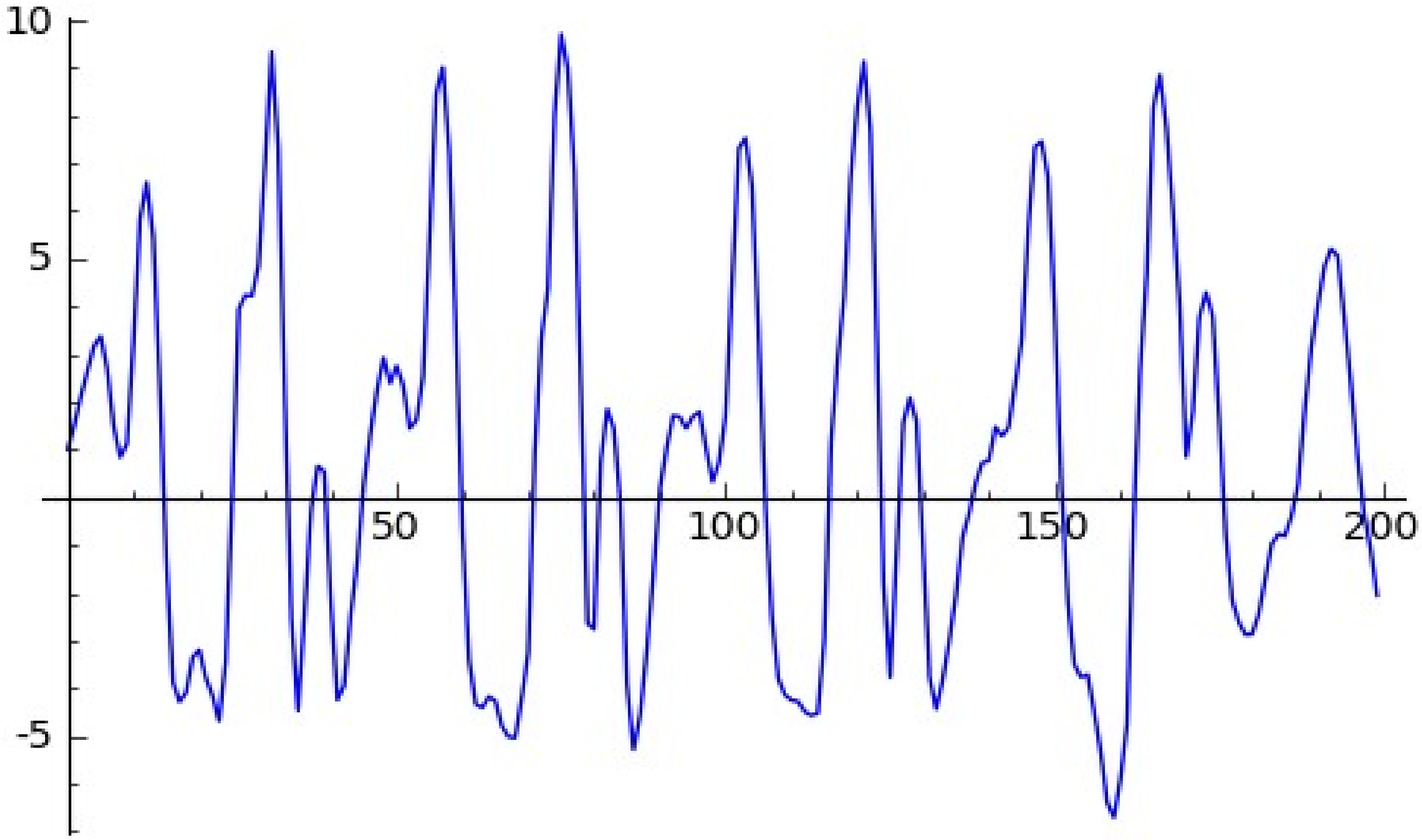
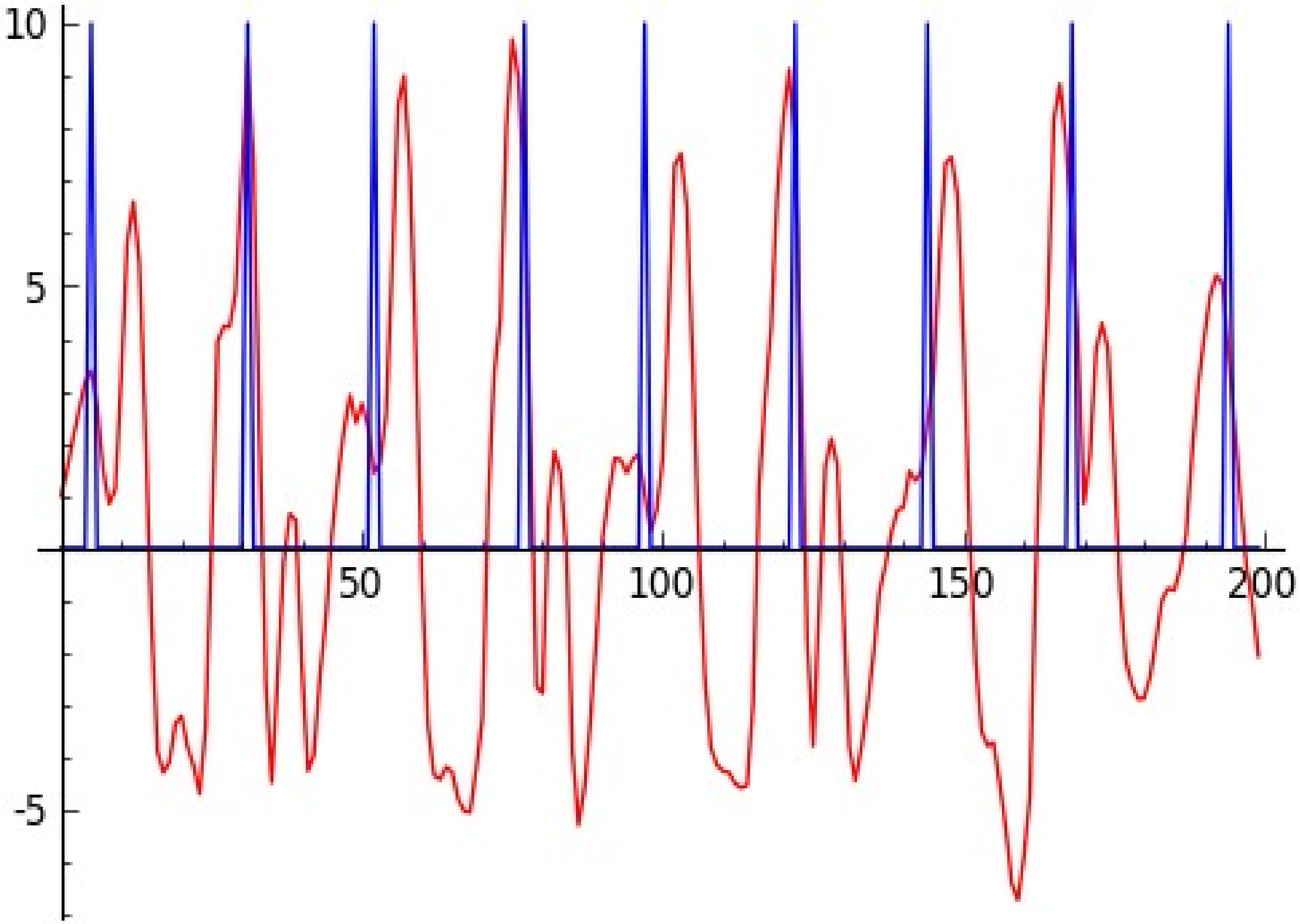
Count the steps!



Absolute value of the a smartphone accelerometer signal when the subject was walking, device in the pocket.

Not that easy



9 steps!

Why PLL?

- Phase-locked loops (PLL) have been used successfully in telecommunication to extract periodic signals from noise
- Acceleration signal processing often requires same type of noise tolerance and the movement pattern is often periodic like walking
  - Step recognition may be trivial if the sensor is placed and fixed at “good” locations like shoe heel
  - If the sensor is placed casually, particularly on the torso, the measured signal is the sum of different movement components, e.g. limbs

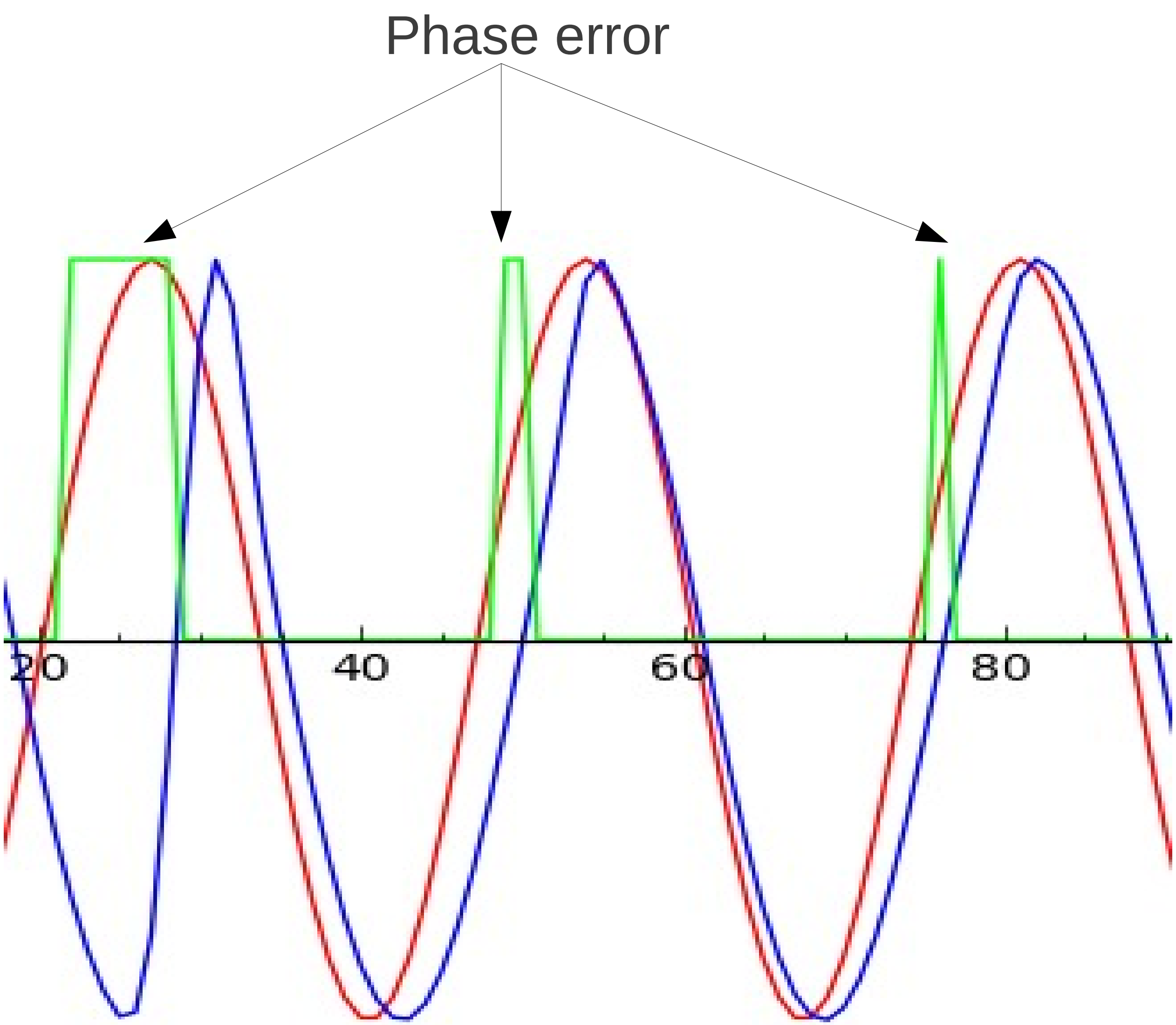
Locking to phase

- PLL reconstructs the original signal with a tunable oscillator
- The oscillator is tuned by the phase difference between the oscillator's signal and the input signal.
  - Oscillator's phase is behind the phase of the input signal → increase the frequency
  - Oscillator's phase is ahead of the phase of the input signal → decrease the frequency
- If the feedback loop is tuned correctly, the oscillator's phase is *locked* onto the input signal's phase → phase-locked loop

Phase detection

- Old analog way: multiplying the input and the oscillator's signal (also called *reference signal*), filter out the higher harmonics → sensitive to input signal amplitude
- Digital phase detectors
  - Digitize both the input and reference signal
  - Generate digital phase error signal
- Our phase detector (adopted from the literature):
  - Principle: “wait for rising edge of the input signal. Then generate phase error signal until the rising edge of the oscillator's signal arrives”

Phase error



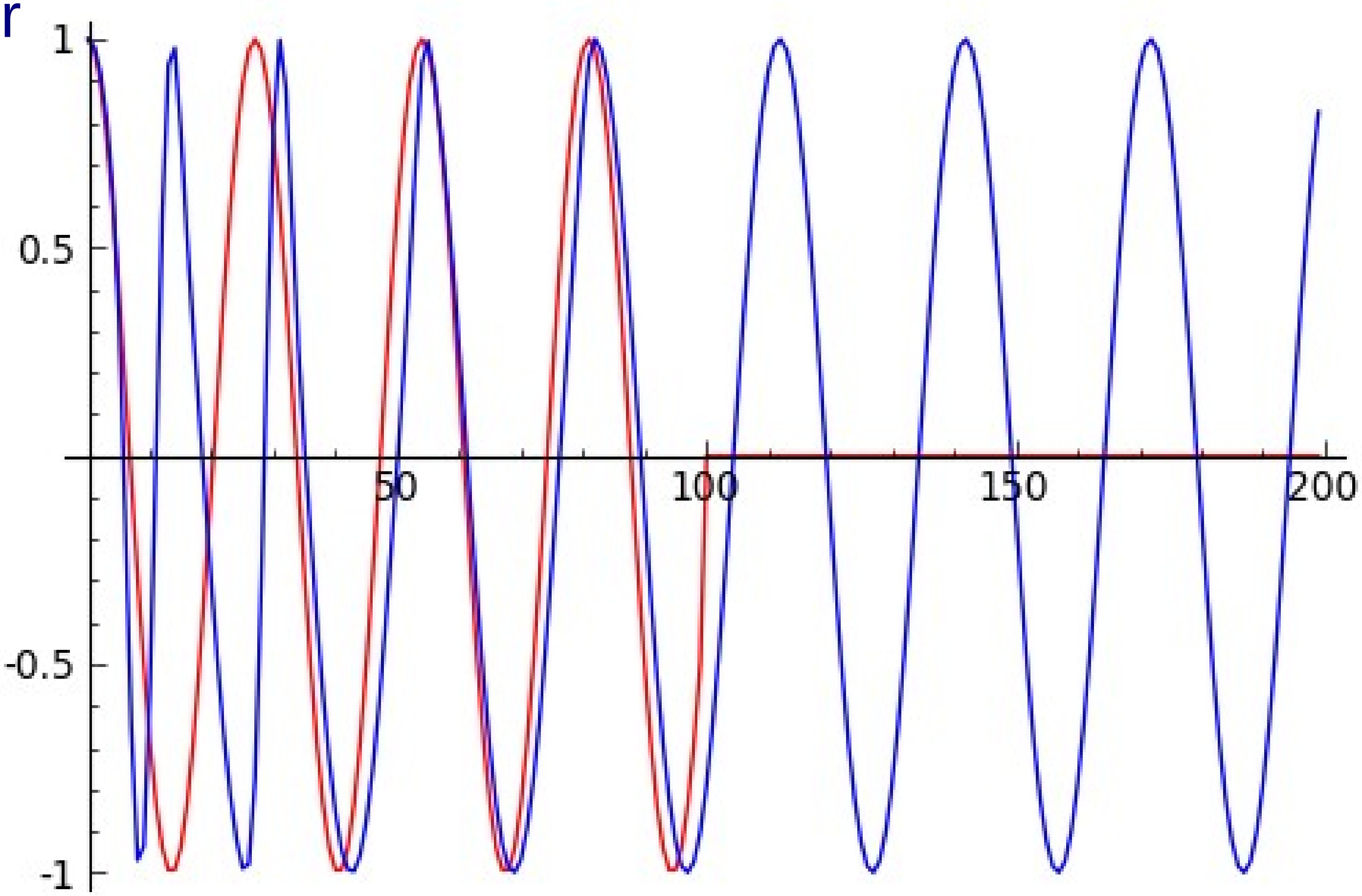
Lock detection

- As long as there is a periodic input signal within the lock range, PLL locks onto the signal
- If there is none, the PLL's oscillator becomes ***free-running***
- We can't count steps in free-running phase, the reference signal then has no relationship with the input signal → lock detection is key

Free-running phase

In lock | Free-running

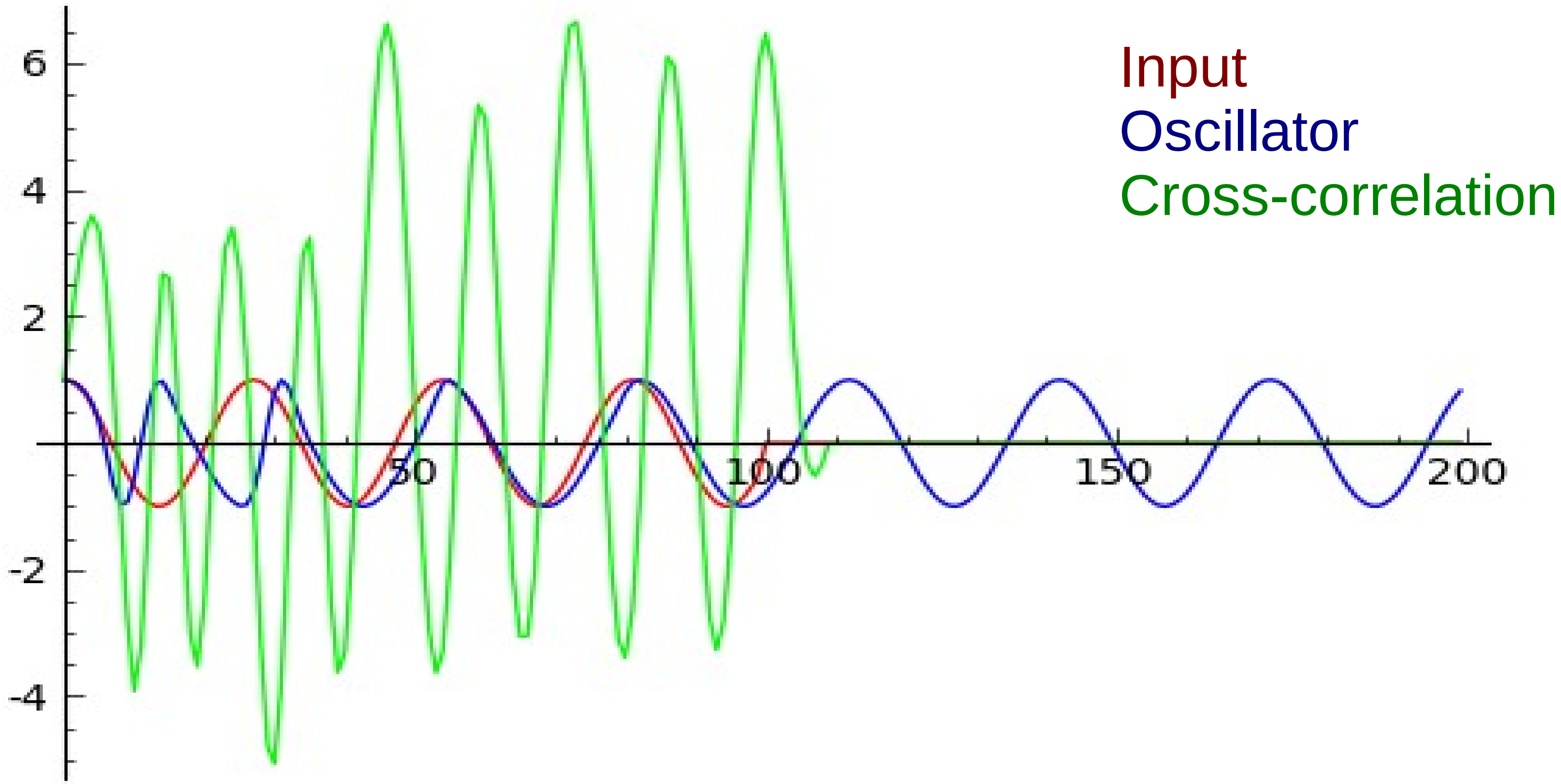
Input
Oscillator



Our lock detector

- A number of lock detectors from the literature were tried, none of them was reliable enough
- Principle our lock detector:
  - Cross-correlate the input and reference signals → this yields “similarity” of the two signals
  - Calculate the average power of the cross-correlation signal for an entire period of the reference signal
  - Compare against threshold

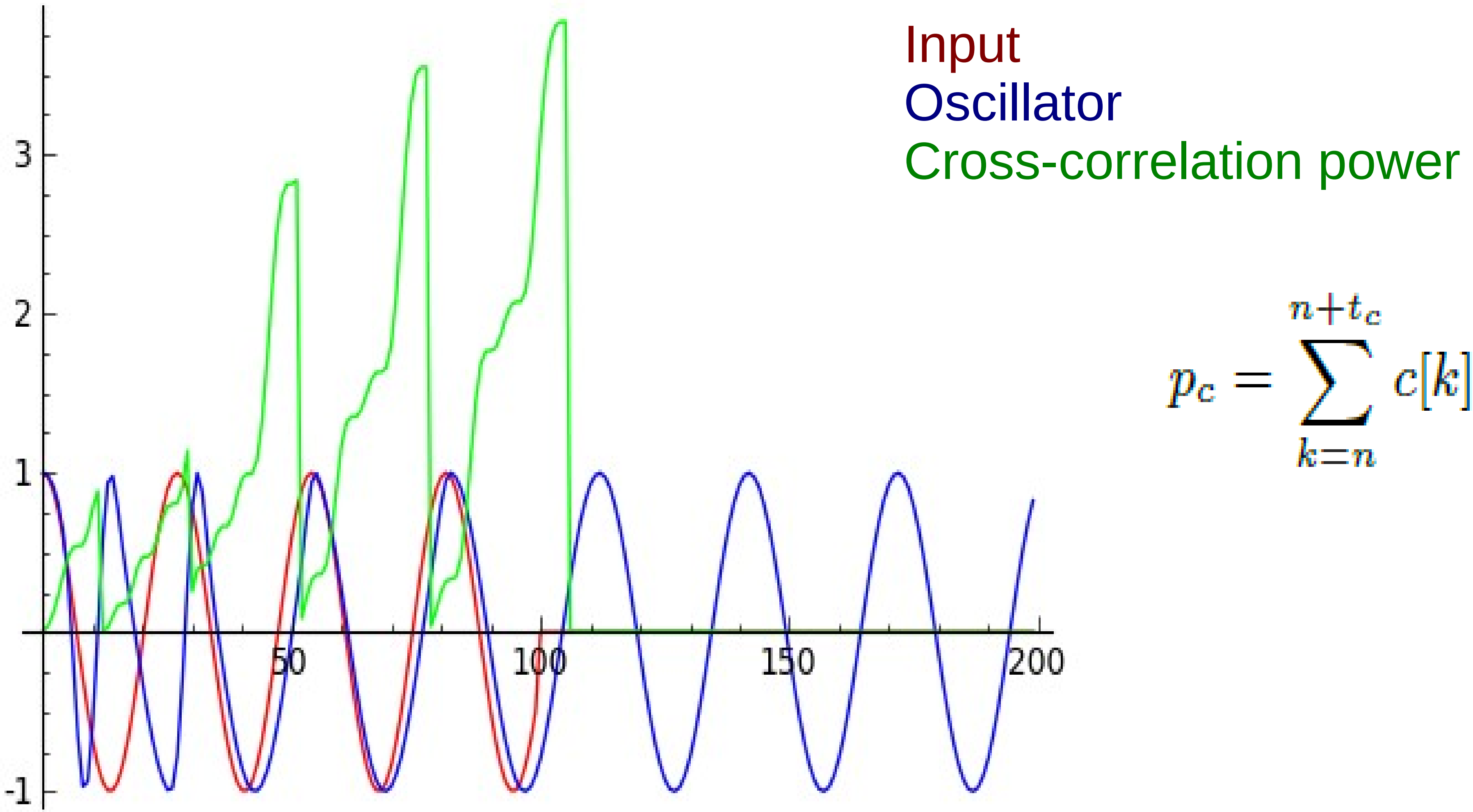
Cross-correlation=similarity



$$c[n] = \sum_{k=0}^{N} a[k+n]y[N-k+n]$$

Power of the cross-correlation signal

Accumulated cross-correlation signal power is large if the PLL is in lock

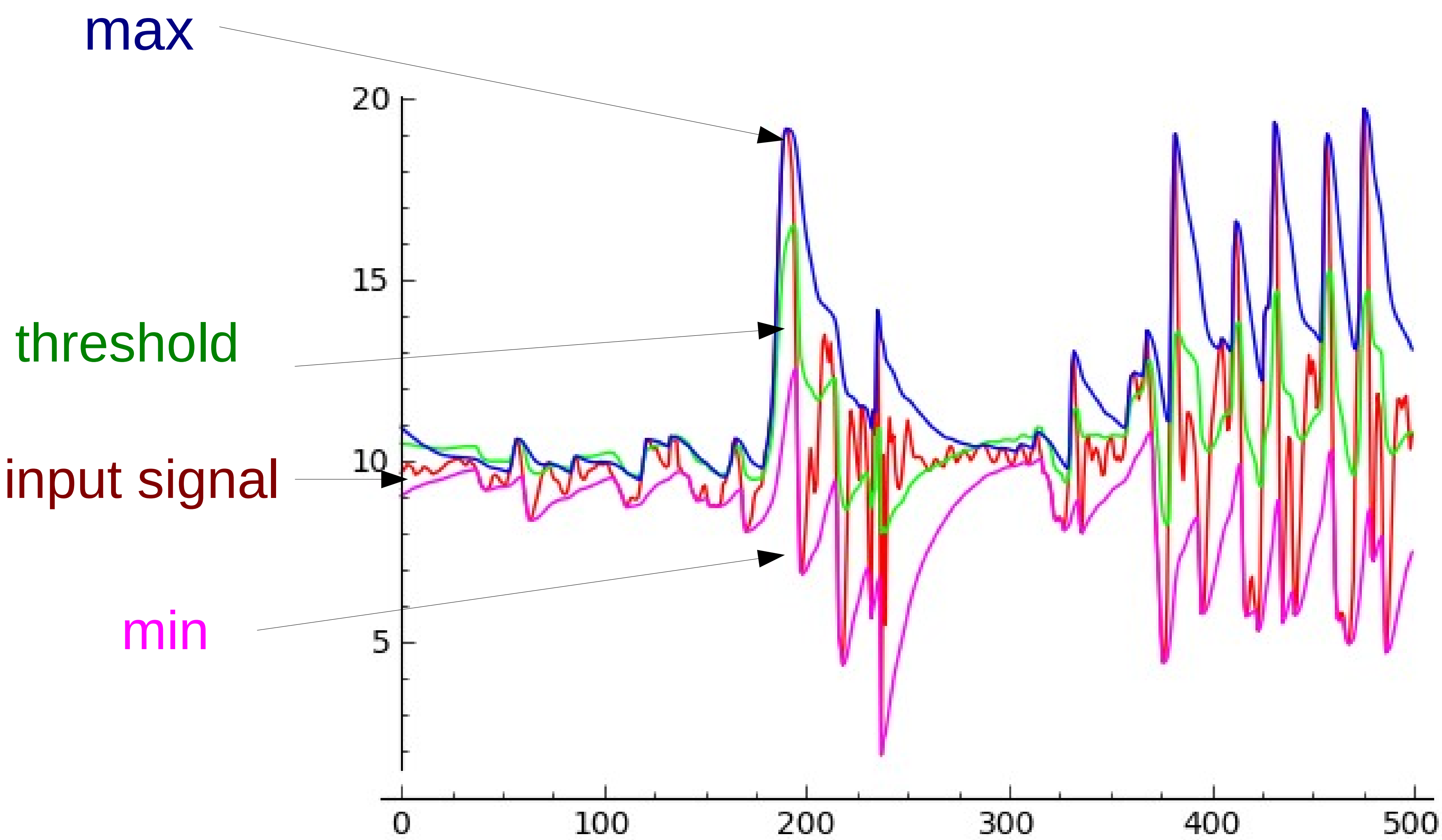


$$p_c = \sum_{k=n}^{n+t_c} c[k]^2$$

Real-world accelerometer signals

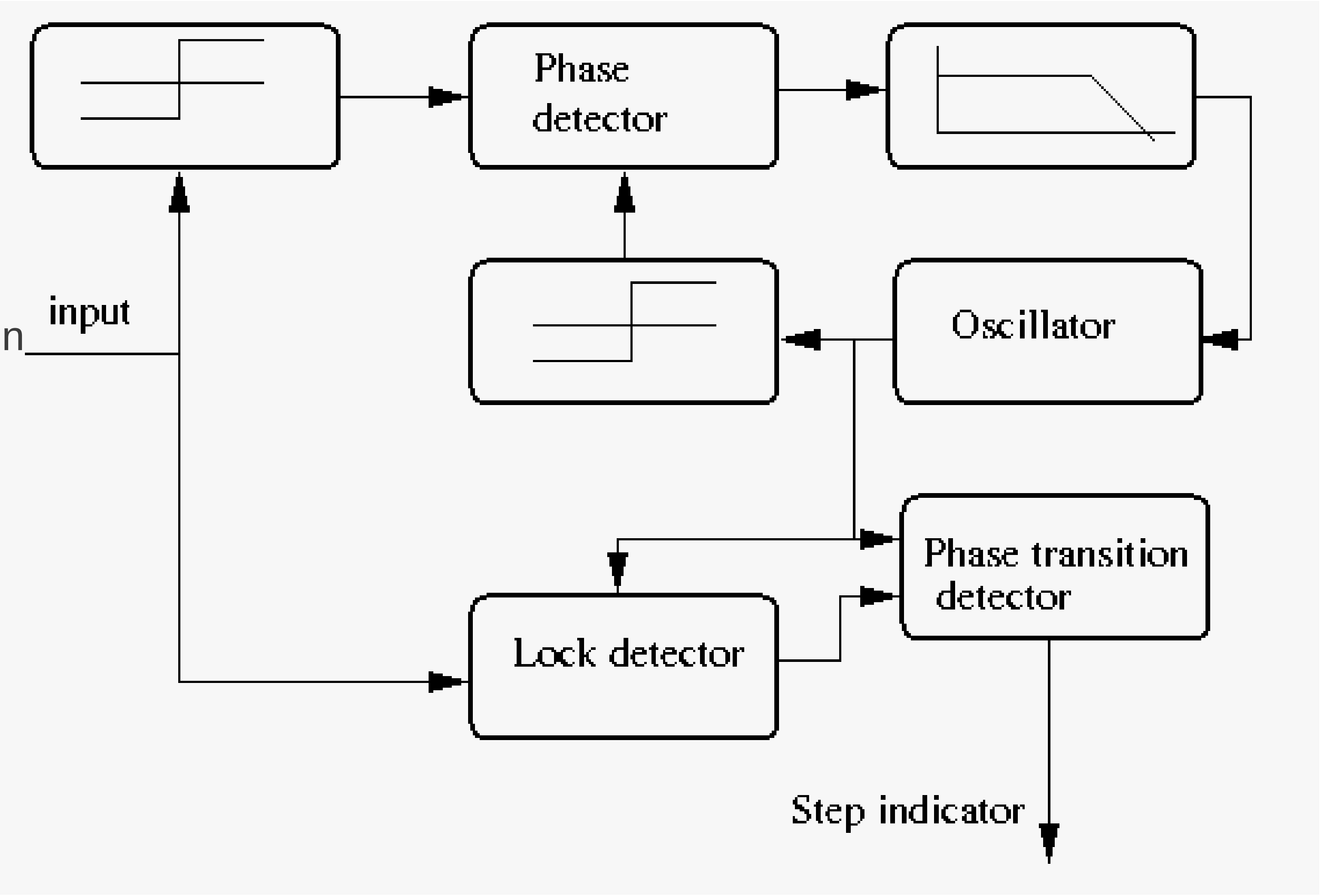
- Typical accelerometer employed in smartphones has 3 axes
- As the phone's position relative to the user's body is unknown, we can use only the acceleration vector's absolute value
- That absolute value has the Earth's acceleration vector added → gravity compensation is needed
- Due to the calibration errors of different accelerometer types, we used adaptive algorithm to figure out the input signal's 0->1 threshold

Threshold adaptation

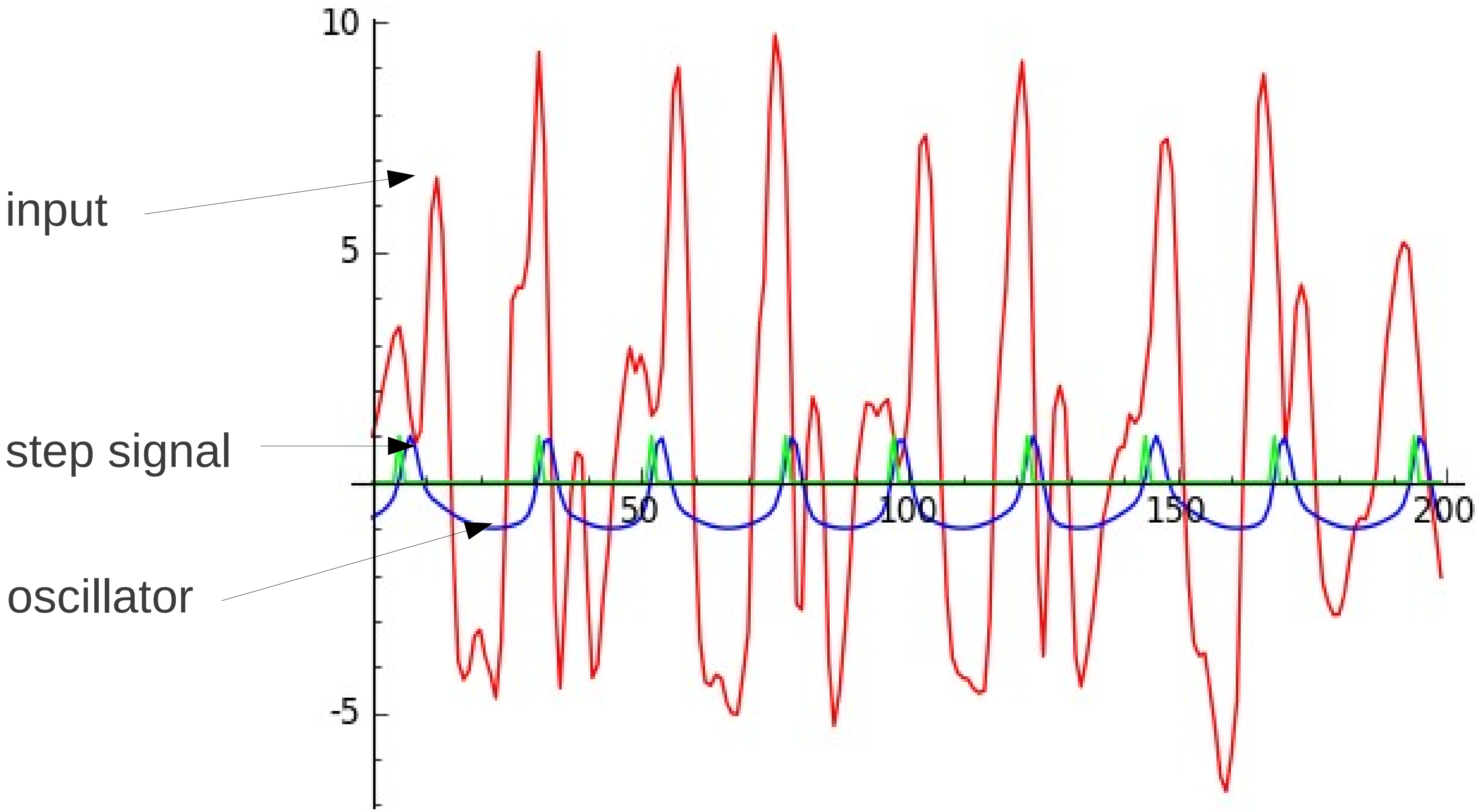


Putting it all together

Absolute
acceleration
value



Tuning



Results

- Prototyped
  - in Sage with recorded samples
  - on Android phones for real-life measurements
- Limited evaluation – infrastructure was not available for exhaustive tests
  - 8 persons, 40-100 steps counted by the person: average error: 2.1% for all the measurements
  - Tested against Bodymedia Sensewear armband, 1 person, 100-200 steps, varied terrain, counted by the person, using the value counted by the person as reference
    - Average error for our prototype: 6.125%
    - Average error for Sensewear: 2.75%

Questions?

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Thank you!