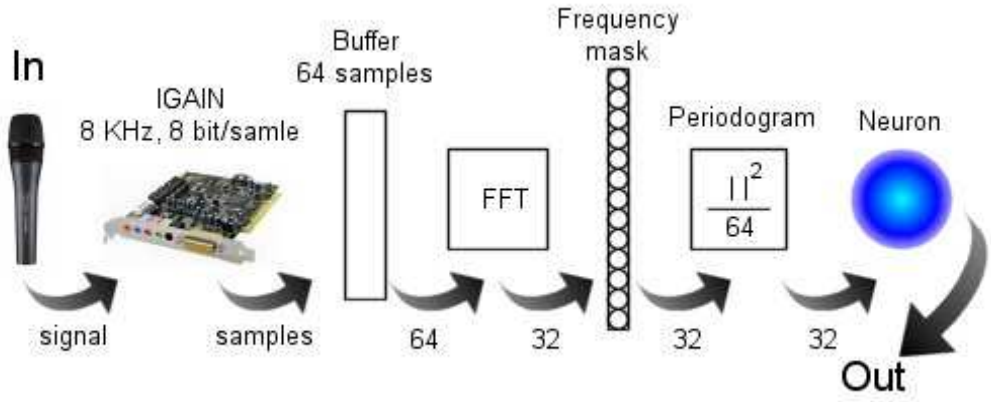
Chapter 1 – System Architecture

1.1 Whistle recognition

System architecture can be explained by the following scheme:



The signal is read from the internal PC's microphone, pre-amplified according to SoundBlaster's input gain (IGAIN), sampled by the SoundBlaster's DSP and saved into a 64-samples buffer.
A sampling frequency of 8 KHz and a sample size of 8 bit/sample turned out to be suitable for the job.
Then, signal is analysed in the frequencies through the periodogram, given by:

$$P_k = \frac{|X_k|^2}{64}$$, where $$X_k = fft(x_n)$$, with k=1,...,32 and n=1,...,64.

A frequency mask has been introduced to save time stopping the calculation for periodogram's samples whose frequencies are far from whistle's ones. Finally, periodogram samples at frequencies of interest become the input of a perceptron, which detects the whistle. The perception's activation function is not a simple sgn(x) function, but hysteresis has been introduced, to avoid spurious commutations in transient situations.

Reading from SoundBlaster

WR simply accesses the SoundBlaster through "/dev/dsp".
The device is opened at startup, its parameters are immediately set (sampling frequency, sample size, size and number of fragments for real-time).
After these operations have been completed, WR starts reading blocks of 64 samples continuously.
Before shutting down, WR closes "/dev/dsp".
[See code: Audio.h]
[See code: Audio.cpp]

The fft

This is the slowest process of the job, so many adjustments have been made to make it faster, by reducing the number of floating-point multiplications which need to be done .
Starting from the DFT formula:

$$X_k = \sum_{n=0}^{N-1} x_n \cdot W_N^{-nk}$$

where:

$0 \leqslant n \leqslant N-1$ is the time index

$0 \leqslant k \leqslant N-1$ is the frequency index

$$W_N = e^{-j \cdot \frac{2\pi}{N}}$$

standard fft (applyable when N is a power of 2) proceeds subdividing the original sequence in 2 sub-sequences:

$$X_k = \sum_{n=0}^{\frac{N}{2}-1} x_{2n} \cdot W_n^{-2nk} + \sum_{n=0}^{\frac{N}{2}-1} x_{2n+1} \cdot W_N^{-(2n+1)k} =$$

$$= \sum_{n=0}^{\frac{N}{2}-1} x_{2n} \cdot W_{\frac{N}{2}}^{-nk} + W_N^{-k} \cdot \sum_{n=0}^{N-1} x_{2n+1} \cdot W_{\frac{N}{2}}^{-nk}$$

since this formula is valid for $0 \leq k \leq N/2 - 1$, a second formula is needed for the second half of the sequence:

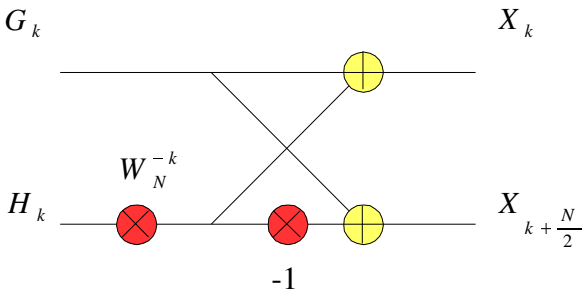
$$X_{k+\frac{N}{2}} = \sum_{n=0}^{\frac{N}{2}-1} x_{2n} \cdot W_{\frac{N}{2}}^{-n\left(k+\frac{N}{2}\right)} + W_N^{-k} \cdot W_N^{-\frac{N}{2}} \cdot \sum_{n=0}^{\frac{N}{2}-1} x_{2n+1} \cdot W_{\frac{N}{2}}^{-n\left(k+\frac{N}{2}\right)} =$$

$$= \sum_{n=0}^{\frac{N}{2}-1} x_{2n} \cdot W_{\frac{N}{2}}^{-nk} - W_N^{-k} \cdot \sum_{n=0}^{N-1} x_{2n+1} \cdot W_{\frac{N}{2}}^{-nk}$$

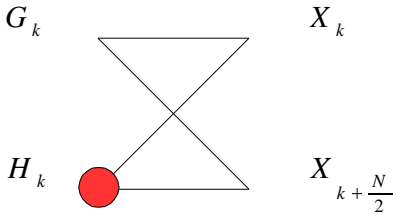
called:

$$G_k = \sum_{n=0}^{\frac{N}{2}-1} x_{2n} \cdot W_{\frac{N}{2}}^{-nk} \quad \text{and} \quad H_k = \sum_{n=0}^{\frac{N}{2}-1} x_{2n+1} \cdot W_{\frac{N}{2}}^{-nk}$$

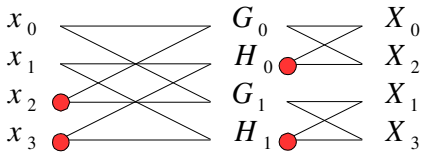
we have:



This scheme is called BUTTERFLY and is usually explained simply by drawing this scheme:



A butterfly contains one complex multiplication ($H_k \times W_N^{-k}$), indicated with the red point.
For istance, we have to do the following process to calculate the DFT of a 4-samples sequence:



So, 4 butterflies must be calculated. Therefore, 4 complex multiplications are needed to complete the job.
But the original sequence can be subdivided in a number m of sub-sequences different from 2 (3,4,5, etc.); obviously N must be a power of m.
A particular case is m = 4:

$$X_k = \sum_{n=0}^{\frac{N}{4}-1} x_{4n} \cdot W_{\frac{N}{4}}^{-nk} + W_N^{-k} \cdot \sum_{n=0}^{\frac{N}{4}-1} x_{4n+1} \cdot W_{\frac{N}{4}}^{-nk} + W_N^{-2k} \cdot \sum_{n=0}^{\frac{N}{4}-1} x_{4n+2} \cdot W_{\frac{N}{4}}^{-nk} + W_N^{-3k} \cdot \sum_{n=0}^{\frac{N}{4}-1} x_{4n+3} \cdot W_{\frac{N}{4}}^{-nk}$$

$$X_{k+\frac{N}{4}} = \sum_{n=0}^{\frac{N}{4}-1} x_{4n} \cdot W_{\frac{N}{4}}^{-nk} + W_N^{-\frac{N}{4}} \cdot W_N^{-k} \cdot \sum_{n=0}^{\frac{N}{4}-1} x_{4n+1} \cdot W_{\frac{N}{4}}^{-nk} + W_N^{-\frac{2 \cdot N}{4}} \cdot W_N^{-2k} \cdot \sum_{n=0}^{\frac{N}{4}-1} x_{4n+2} \cdot W_{\frac{N}{4}}^{-nk} + W_N^{-\frac{3 \cdot N}{4}} \cdot W_N^{-3k} \cdot \sum_{n=0}^{\frac{N}{4}-1} x_{4n+3} \cdot W_{\frac{N}{4}}^{-nk}$$

$$X_{k+\frac{2N}{4}} = \sum_{n=0}^{\frac{N}{4}-1} x_{4n} \cdot W_{\frac{N}{4}}^{-nk} + W_N^{-2 \cdot \frac{N}{4}} \cdot W_N^{-k} \cdot \sum_{n=0}^{\frac{N}{4}-1} x_{4n+1} \cdot W_{\frac{N}{4}}^{-nk} + W_N^{-2 \cdot \frac{2 \cdot N}{4}} \cdot W_N^{-2k} \cdot \sum_{n=0}^{\frac{N}{4}-1} x_{4n+2} \cdot W_{\frac{N}{4}}^{-nk} + W_N^{-2 \cdot \frac{3 \cdot N}{4}} \cdot W_N^{-3k} \cdot \sum_{n=0}^{\frac{N}{4}-1} x_{4n+3} \cdot W_{\frac{N}{4}}^{-nk}$$

$$X_{k+\frac{3N}{4}} = \sum_{n=0}^{\frac{N}{4}-1} x_{4n} \cdot W_{\frac{N}{4}}^{-nk} + W_N^{-3 \cdot \frac{N}{4}} \cdot W_N^{-k} \cdot \sum_{n=0}^{\frac{N}{4}-1} x_{4n+1} \cdot W_{\frac{N}{4}}^{-nk} + W_N^{-3 \cdot \frac{2 \cdot N}{4}} \cdot W_N^{-2k} \cdot \sum_{n=0}^{\frac{N}{4}-1} x_{4n+2} \cdot W_{\frac{N}{4}}^{-nk} + W_N^{-3 \cdot \frac{3 \cdot N}{4}} \cdot W_N^{-3k} \cdot \sum_{n=0}^{\frac{N}{4}-1} x_{4n+3} \cdot W_{\frac{N}{4}}^{-nk}$$

Calling:

$$G_k = \sum_{n=0}^{\frac{N}{4}-1} x_{4n} \cdot W_{\frac{N}{4}}^{-nk}$$

$$H_k = \sum_{n=0}^{\frac{N}{4}-1} x_{4n+1} \cdot W_{\frac{N}{4}}^{-nk}$$

$$L_k = \sum_{n=0}^{\frac{N}{4}-1} x_{4n+2} \cdot W_{\frac{N}{4}}^{-nk}$$

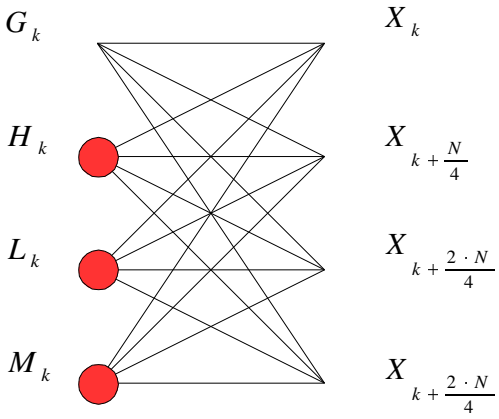
$$M_k = \sum_{n=0}^{\frac{N}{4}-1} x_{4n+3} \cdot W_{\frac{N}{4}}^{-nk}$$

We have the following situation:

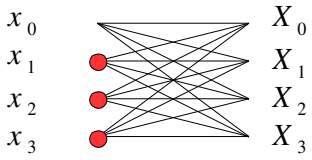
$$\begin{bmatrix} X_k \\ X_{k+\frac{N}{4}} \\ X_{k+2\cdot\frac{N}{4}} \\ X_{k+3\cdot\frac{N}{4}} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & W_N^{-\frac{N}{4}} & W_N^{-\frac{2\cdot N}{4}} & W_N^{-\frac{3\cdot N}{4}} \\ 1 & W_N^{-2\cdot\frac{N}{4}} & W_N^{-2\cdot\frac{2\cdot N}{4}} & W_N^{-2\cdot\frac{3\cdot N}{4}} \\ 1 & W_N^{-3\cdot\frac{N}{4}} & W_N^{-3\cdot\frac{2\cdot N}{4}} & W_N^{-3\cdot\frac{3\cdot N}{4}} \end{bmatrix} \cdot \begin{bmatrix} G_k \\ W_N^{-k} \cdot H_k \\ W_N^{-2k} \cdot L_k \\ W_N^{-3k} \cdot M_k \end{bmatrix} =$$

$$= \underbrace{\begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -j & -1 & +j \\ +1 & -1 & +1 & -1 \\ +1 & +j & -1 & -j \end{bmatrix}}_{\underline{W}_N} \cdot \begin{bmatrix} G_k \\ W_N^{-k} \cdot H_k \\ W_N^{-2k} \cdot L_k \\ W_N^{-3k} \cdot M_k \end{bmatrix}$$

which can be summarized with:



This butterfly requires 3 complex multiplications: W_N matrix can be calculated without any multiplication.
Applying this butterfly to a 4-samples sequence yields:
$G_K = \{x_O\}$, $H_K = \{x_1\}$, $L_K = \{x_2\}$, $M_K = \{x_3\}$ and:



Only one butterfly is needed; so we complete the job with 3 complex multiplications, while 4 multiplications were used with the standard butterfly.
Therefore, using 4 sub-sequences will result in a (theorical) 25% gain in working time.
This method is fully supported in WR, as it operates on 64-samples sequences, were $64 = 4^3$.
Now, symmetry property of DFT can be used to save even more time.
Actually WR operates on real sequences (sampled audio), and the following property is verified:

$$X_k = X^*_{-k} \Rightarrow \Re(X_k) = \Re(X_{-k}) \quad \text{and} \quad \Im(X_k) = -\Im(X_{-k})$$

But two real-sequence DFTs can be obtained from a single DFT of a complex sequence, which is built as follows:

$$s_n = x_n + j \cdot y_n \quad ,$$

where x_n and y_n are real sequences of the same length.
Transforming s_n we have:

$$S_k = \Re(X_k) - \Im(Y_k) + j \cdot [\Im(X_k) + \Re(Y_k)]$$

But:

$$\begin{aligned} S_k + S_{-k} &= \Re(X_k) - \Im(Y_k) + j \cdot [\Im(X_k) + \Re(Y_k)] + \Re(X_{-k}) - \Im(Y_{-k}) + \\ &+ j \cdot [\Im(X_{-k}) + \Re(Y_{-k})] = \\ &= \Re(X_k) - \Im(Y_k) + j \cdot [\Im(Y_k) + \Re(Y_k)] + \Re(X_k) + \Im(Y_k) + \\ &+ j \cdot [-\Im(X_k) + \Re(Y_k)] = 2 \cdot \Re(X_k) + 2j \cdot \Re(Y_k) \end{aligned}$$

$$\begin{aligned} S_k - S_{-k} &= \Re(X_k) - \Im(Y_k) + j \cdot [\Im(X_k) + \Re(Y_k)] - \Re(X_{-k}) + \Im(Y_{-k}) - \\ &- j \cdot [\Im(X_{-k}) + \Re(Y_{-k})] = \\ &= \Re(X_k) - \Im(Y_k) + j \cdot [\Im(X_k) + \Re(Y_k)] - \Re(X_k) - \Im(Y_k) + \\ &+ j \cdot [\Im(X_k) - \Re(Y_k)] = -2 \cdot \Im(Y_k) + 2j \cdot \Im(X_k) \end{aligned}$$

So X_K and Y_K can be rebuilt with the following formulas:

$$\Re(X_k) = \frac{1}{2} \cdot [\Re(S_k) + \Re(S_{-k})] \quad , \quad \Im(X_k) = \frac{1}{2} \cdot [\Im(S_k) - \Im(S_{-k})]$$

$$\Re(Y_k) = \frac{1}{2} \cdot [\Im(S_k) + \Im(S_{-k})] \quad , \quad \Im(Y_k) = \frac{1}{2} \cdot [\Re(S_{-k}) - \Re(S_k)]$$

By doing this way, we obtain a (theorical) 50% of gain in work time.
[See code: Bars.h]
[See code: Bars.cpp]

Data separation
Some periodogram's samples are far from the whistle's frequency and a recognition based on those samples will result in a low-quality one. Therefore, the correct frequencies must be selected. Correct frequencies are those that best separate whistle samples from noise ones.
Data separation is an index used to decide how much a periodogram's sample is good separating whistle from noise. For each periodogram's sample, Data Separation is calculated as follows:

$$S_k = 1 - \frac{(W_k \cap N_k)}{(W_k \cup N_k)}, 1 \leqslant k \leqslant 32$$

where W_k and N_k are sets of values obtained from the k-th periodogram's samples generated by 64-samples blocks of whistle or noise, respectively.

Frequency Mask and Periodogram

Not every periodogram samples are to be considered for the recognition, and only selected samples must be passed as an input to the perceptron.
Frequency mask is a simple blocking mechanism implemented with a 32-bit structure: each bit of the structure determines whether corresponding sample is passed or not to the perceptron.
If a sample must be discharged, it shouldn't be calculated at all: for this reason, frequency mask has been introduced before the periodogram ($|\bullet|^2/64$) calculation.
More multiplications could be avoided integrating frequency mask in the fft by blocking discharged samples before being calculated.
This mechanism is quite difficult and has not been implemented, as fft work time is acceptable.
Finally, interesting periodogram samples are calculated, while the other samples are forced to 0.
[See code: FreqMask.h]

Doppler effect

The frequency skew introduced by doppler effect can be easily estimated with an analysis based on acoustic theory:
We know that:
1) If source moves in air while the observer is still, the heard frequency is:

$$f_{Observer} = \frac{f_0}{1 - (\frac{v_{source}}{v_{sound}}) \cdot \cos(\theta)}$$

2) If the source is still and the observer moves in air, the heard frequency is:

$$f_{Observer} = f_0 \cdot [1 - (\frac{v_{observer}}{v_{sound}}) \cdot \cos(\theta)]$$

But both the source (whistle) and the observer (robot) move in air; we can obtain the correct formula considering two paths: from whistle to a still point P (using formula 1) and from P to the robot (using formula 2).
In this way it yields:

$$f_{robot} = [1 - (\frac{v_{observer}}{v_{sound}}) \cdot \cos(\theta)] \cdot f_P = \frac{1 - (\frac{v_{observer}}{v_{sound}}) \cdot \cos(\theta)}{1 - (\frac{v_{source}}{v_{sound}}) \cdot \cos(\theta)} \cdot f_{whistle}$$

Sound speed in air is experimentally set to 331.6 m/s at 0K, and it rises with the square root of the temperature, in K.
At room temperature, we have:

$$v_{sound}(25\,^\circ C) = 331.6 \cdot \sqrt{\frac{297}{273}}\, m/s = 345.86\, m/s$$

Assuming:

$v_{source} = 5\, m/s$ (a man running)
$v_{observer} = 2\, m/s$ (robot speed)
$f_{wistle} \simeq 3\, KHz$ (extimated from recorded samples)

the worst-case skew in frequency can be optained by:

$$\Delta f_{robot} = \frac{1 \pm \frac{5\ m/s}{346\ m/s}}{1 \mp \frac{2\ m/s}{346\ m/s}} \cdot 3\ KHz - 3\ KHz \simeq \pm 61\ Hz$$

But periodogram can be modelled with a bank of band-pass filters whose bandwitch is

$$B = 4\frac{KHz}{32} = 125\ Hz$$

So, frequency skew can be a 50% of period gram resolution and the whistle frequency can be moved to the next or previous period gram sample by Doppler effect.
For this reason, perceptron uses a non-linear activation function and can extend its frequency mask upon a sample forward or backward.

Output perceptron with hysteresis

WR uses a non-linear perceptron, in order to leave his behaviour unchanged even if doppler effect shifts whistle's frequency.
If a whistle rises sample i of the periodogram, Doppler effect can cause sample i to remain low and sample (i+1) or (i-1) to rise instead.
This suggests to use an activation function based on distance from origin, like a sphere, instead of a simple plane.
WR uses an ellipsoidal surface: if a point is internal to the surface, it would be recognised as noise, otherwise it would be recognised as whistle.
The introduction of hysteresis brings the division of the ellipsoid into two ellipsoids that identify noise->whistle (turn-on) and whistle->noise (turn-off) thresholds.
The non-linear surface is described as follows:

$$\sum_{n=1}^{32} \left(\frac{x_n}{W_n}\right)^2 = s$$, where $x_1 ... x_{32}$ are inputs and $W_1 ... W_{32}$ are perceptron's weights.

So, the activation function (with hysteresis) is:

$$\begin{cases} Out = -1 \begin{cases} +1 & , if \sum_{n=0}^{32} \left(\frac{x_n}{W_n}\right)^2 > 10^{\frac{s_0}{10}} \\ -1 & , otherwise \end{cases} \\ Out = +1 \begin{cases} -1 & , if \sum_{n=0}^{32} \left(\frac{x_n}{W_n}\right)^2 \leqslant 10^{\frac{s_1}{10}} \\ +1 & , otherwise \end{cases} \end{cases}$$

, where +1=Whistle and -1=Noise

Turn-on and turn-off tresholds are defined in dB:

$$s_{01} = 10 \cdot \mathrm{Log}(s_{turnon}) \quad \text{and} \quad s_{10} = 10 \cdot \mathrm{Log}(s_{turnoff})$$

The perceptron's learning function always acts with turn-on and turn-off thresholds that have been forced to 0 and finds a suitable weight vector.
Once an optimal vector has been found, the user can introduce hysteresis.
Learning rule for this perceptron is the following:

$$error = \frac{1}{2} \cdot (desired\ output - perceptron\ 's\ output)$$

$W_k = W_k - \gamma \cdot x_k \cdot error$, where $0 \leqslant \gamma \leqslant 0.1$ is the learning rate.

Actually, if error is -1 , it means that perceptron outputted +1 (whistle) when it should output -1 (Noise).
So, a noise point, which must be internal to the ellipsoid, resulted external.
Since W_k is the ellipsoid's radius on k axis, this weight must be raised to let the ellipsoid include the example.
Doing the inverse reasoning, it is easy to understand that the weight should be lowered if error = +1.
Combining the two cases, we obtain the learning rule which was previously discussed, where the weight is adjusted proportionally to the relative perceptron's input in the same direction.
Values of the learning rate from 0 to 0.1 have been chosen to slow down the learning loop in order to let the user see the weight vector changing through a graphical representation.
Learning rate can be greater than 0.1, nevertheless values greater than 0.9 caused on some example sets large oscillations, preventing the reaching of the optimal weight vector.

[See code: Perc.h]
[See code: Perc.cpp]

1.2 Whistle counter

Description
The whistle counter module is directly connected to the perceptron's output and it implements a fast algorithm, which detects whistle's length and multiplicity.
Output of this algorithm are:
Short whistle
Long whistle
Multiple whistle (double, triple, and so on...)

Whistle time specifics
WR requires the user to define a set of parameters to determine what kind of whistle has been played.
In particular:
- Time step: It defines the period of the main WR's timer, in milliseconds.
- Short if <: The maximum length of a short whistle.
- Long if >: The minimum length of a long whistle.
- Interval <: The maximum length of the interval between two whistles to consider them part of a multiple whistle.
- Whistle minimum length: The minimum length of a valid whistle.
- Noise minimum length: The minimum length of a valid noise.

[See file: TimeSpecStruct.h]

The algorithm
The most important feature of the algorithm is speed.
For this reason, the chosen algorithm only reads the current perceptron's output and stores all the previous states through a very small stack (5 bytes).
Input of the algorithm is the perceptron's state (+1=whistle, -1=noise).
Output of the algorithm is the message type (short, long, double, triple, ...)
The algorithm also containes an internal Reliability control, based on how many times the stack must be corrected to transform received signal in an ideal whistle's one.
A particular case is that of a single whistle, which length is between the maximum length of a short whistle and the minimum length of a long whistle; when it happens, the closest solution (short or long) is taken, but reliability is forced to 80%.

How the algorithm works
Heart of the algorithm is the “Process” function.
Every time it is called (by the main WR's timer) it:

- stores the previous input (whistle or noise)
- compares the current input with the previous one and updates the stack.
- when a whistle is terminated and a long interval follows it (long means that it is greater than the one specified by the "Interval <" field), it sends a message.

The stack stpres a list of events: an event is a whistle(W) or a noise(N), followed by its length, in time steps.
For instance, a 150ms whistle will be translated in a "W-15" event, using a 10ms time step, or in a "W-6" event, using a 25ms timestep; the same rule is valid for noise using "N" in spite of "W".
Every time the current input equals the previous one, the current event on the stack increments its length; lengths greater than 127 steps will be clamped to 127.
When the input changes, the current event is pushed in the stack and a new event is created; obviously, the new event will be a "N" event if the current inout is -1, or a "W" event otherwise.
Doing this operation, the algorithm controls the validity of the current event, before pushing it: if the event is not valid, it will not be pushed, but it will be considered part of the previous event and its length will be added to the previous event's one; in this case, the current event is popped from the stack.
For instance, the "W-3" events in fig. 4.1 are not valid, since their length is smaller than the one defined in the "Minimum whistle's length" field, so they are eliminated.
A similar case can be seen in fig. 4.2, where the "N-1" event is eliminated.
Each time an event is eliminated, reliability is reduced to signal that an error occourred.
This is the basic mechanism: the cost is small because the work can be done with a few comparisons and increments.
But, as the first event is forced to "infinite noise" (or "N-127"), a triple whistle requires only a 7-wide stack (N W N W N W N), but if we want the algorithm to recognise a series of 100 whistles, we will need a 201-wide stack!
To correct this problem, a variable multiplicity has been introducted (mNumWhistles), and the stack is collapsed to consider only the last whistle.
Fig. 4.3 is a good example of this mechanism.
A first whistle is stored in stack[1]; the second whistle grows in stack[3]; when the second interval begins and the algorithm knows that the "W" event in stack[3] is a valid whistle, multiplicity (shown as nW in the table) is incremented and the "W" event is copied in stack[1], freeing space for the following whistles.
The new interval grows in stack[2] and can be regularly popped into stack[1] if it is an invalid noise.
After a long interval (greater than that specified through the "Interval <" field), the algorithm returns a non-zero value which represents the message to be sent: if the multiplicity is 1, the length of the whistle is read in order to determine wether to send the "Short Whistle" or the "Long Whistle" message; if multiplicity is greater than 1, it will be directly returned.
Doing this way, the return value will be "Short Whistle", "Long Whistle", or the multiplicity of the whistle; so , 2 means a double whistle, 3 means a triple whistle, and so on...
Following tables are the output from WRTeacher, compiling the counter module in test mode.
The first field is the input from the perceptron, the part is a shot of the current stack, nW is the current multiplicity, the last field is the current reliability.

```
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 1.00
 +1   --->   0: N-127   1: W-  1   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 1.00
 +1   --->   0: N-127   1: W-  2   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 1.00
 +1   --->   0: N-127   1: W-  3   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 1.00
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.98
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.98
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.98
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.98
 +1   --->   0: N-127   1: W-  1   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.98
 +1   --->   0: N-127   1: W-  2   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.98
 +1   --->   0: N-127   1: W-  3   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.98
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 -1   --->   0: N-127   1: ?-???   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 +1   --->   0: N-127   1: W-  1   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 +1   --->   0: N-127   1: W-  2   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 +1   --->   0: N-127   1: W-  3   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 +1   --->   0: N-127   1: W-  4   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 +1   --->   0: N-127   1: W-  5   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 +1   --->   0: N-127   1: W-  6   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 +1   --->   0: N-127   1: W-  7   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
 +1   --->   0: N-127   1: W-  8   2: ?-???   3: ?-???   4: ?-???       nW: 0    Reliability: 0.96
```

```
+1   --->   0: N-127    1: W-  9    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.96
+1   --->   0: N-127    1: W- 10    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N-  1    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N-  2    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N-  3    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N-  4    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N-  5    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N-  6    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N-  7    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N-  8    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N-  9    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N- 10    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N- 11    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N- 12    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N- 13    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N- 14    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: W- 10    2: N- 15    3: ?-???    4: ?-???        nW: 1     Reliability: 0.96
-1   --->   0: N-127    1: ?-???    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
```

Fig.1.1 two invalid whistles followed by a (valid) short whistle

```
-1   --->   0: N-127    1: ?-???    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W-  1    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W-  2    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W-  3    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W-  4    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W-  5    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W-  6    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W-  7    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W-  8    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W-  9    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 10    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 11    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 12    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 13    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 14    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 15    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 16    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 17    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 18    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 19    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 20    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 21    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 22    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 23    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 24    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 25    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 26    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 27    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 28    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 29    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 30    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 31    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 32    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 33    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 34    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 35    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 36    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 37    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 38    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 39    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 40    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
+1   --->   0: N-127    1: W- 41    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 1.00
-1   --->   0: N-127    1: W- 41    2: N-  1    3: ?-???    4: ?-???        nW: 1     Reliability: 1.00
+1   --->   0: N-127    1: W- 43    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 44    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 45    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 46    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 47    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 48    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 49    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 50    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 51    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 52    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 53    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 54    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 55    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 56    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 57    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 58    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 59    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 60    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 61    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 62    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 63    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 64    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 65    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 66    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 67    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 68    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 69    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 70    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 71    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 72    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 73    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 74    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 75    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 76    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
+1   --->   0: N-127    1: W- 77    2: ?-???    3: ?-???    4: ?-???        nW: 0     Reliability: 0.98
-1   --->   0: N-127    1: W- 77    2: N-  1    3: ?-???    4: ?-???        nW: 1     Reliability: 0.98
-1   --->   0: N-127    1: W- 77    2: N-  2    3: ?-???    4: ?-???        nW: 1     Reliability: 0.98
```

```
    -1   --->   0: N-127    1: W- 77    2: N-  3    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: W- 77    2: N-  4    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: W- 77    2: N-  5    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: W- 77    2: N-  6    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: W- 77    2: N-  7    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: W- 77    2: N-  8    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: W- 77    2: N-  9    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: W- 77    2: N- 10    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: W- 77    2: N- 11    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: W- 77    2: N- 12    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: W- 77    2: N- 13    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: W- 77    2: N- 14    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: W- 77    2: N- 15    3: ?-???    4: ?-???         nW: 1     Reliability: 0.98
    -1   --->   0: N-127    1: ?-???    2: ?-???    3: ?-???    4: ?-???         nW: 0     Reliability: 1.00
```

Fig.1.2 a valid long whistle with a small imperfection

```
    -1   --->   0: N-127    1: ?-???    2: ?-???    3: ?-???    4: ?-???         nW: 0     Reliability: 1.00
    +1   --->   0: N-127    1: W-  1    2: ?-???    3: ?-???    4: ?-???         nW: 0     Reliability: 1.00
    +1   --->   0: N-127    1: W-  2    2: ?-???    3: ?-???    4: ?-???         nW: 0     Reliability: 1.00
    +1   --->   0: N-127    1: W-  3    2: ?-???    3: ?-???    4: ?-???         nW: 0     Reliability: 1.00
    +1   --->   0: N-127    1: W-  4    2: ?-???    3: ?-???    4: ?-???         nW: 0     Reliability: 1.00
    +1   --->   0: N-127    1: W-  5    2: ?-???    3: ?-???    4: ?-???         nW: 0     Reliability: 1.00
    +1   --->   0: N-127    1: W-  6    2: ?-???    3: ?-???    4: ?-???         nW: 0     Reliability: 1.00
    +1   --->   0: N-127    1: W-  7    2: ?-???    3: ?-???    4: ?-???         nW: 0     Reliability: 1.00
    -1   --->   0: N-127    1: W-  7    2: N-  1    3: ?-???    4: ?-???         nW: 1     Reliability: 1.00
    -1   --->   0: N-127    1: W-  7    2: N-  2    3: ?-???    4: ?-???         nW: 1     Reliability: 1.00
    -1   --->   0: N-127    1: W-  7    2: N-  3    3: ?-???    4: ?-???         nW: 1     Reliability: 1.00
    -1   --->   0: N-127    1: W-  7    2: N-  4    3: ?-???    4: ?-???         nW: 1     Reliability: 1.00
    -1   --->   0: N-127    1: W-  7    2: N-  5    3: ?-???    4: ?-???         nW: 1     Reliability: 1.00
    -1   --->   0: N-127    1: W-  7    2: N-  6    3: ?-???    4: ?-???         nW: 1     Reliability: 1.00
    -1   --->   0: N-127    1: W-  7    2: N-  7    3: ?-???    4: ?-???         nW: 1     Reliability: 1.00
    -1   --->   0: N-127    1: W-  7    2: N-  8    3: ?-???    4: ?-???         nW: 1     Reliability: 1.00
    -1   --->   0: N-127    1: W-  7    2: N-  9    3: ?-???    4: ?-???         nW: 1     Reliability: 1.00
    -1   --->   0: N-127    1: W-  7    2: N- 10    3: ?-???    4: ?-???         nW: 1     Reliability: 1.00
    -1   --->   0: N-127    1: W-  7    2: N- 11    3: ?-???    4: ?-???         nW: 1     Reliability: 1.00
    -1   --->   0: N-127    1: W-  7    2: N- 12    3: ?-???    4: ?-???         nW: 1     Reliability: 1.00
    +1   --->   0: N-127    1: W-  7    2: N- 12    3: W-  1    4: ?-???         nW: 1     Reliability: 1.00
    +1   --->   0: N-127    1: W-  7    2: N- 12    3: W-  2    4: ?-???         nW: 1     Reliability: 1.00
    +1   --->   0: N-127    1: W-  7    2: N- 12    3: W-  3    4: ?-???         nW: 1     Reliability: 1.00
    +1   --->   0: N-127    1: W-  7    2: N- 12    3: W-  4    4: ?-???         nW: 1     Reliability: 1.00
    +1   --->   0: N-127    1: W-  7    2: N- 12    3: W-  5    4: ?-???         nW: 1     Reliability: 1.00
    +1   --->   0: N-127    1: W-  7    2: N- 12    3: W-  6    4: ?-???         nW: 1     Reliability: 1.00
    +1   --->   0: N-127    1: W-  7    2: N- 12    3: W-  7    4: ?-???         nW: 1     Reliability: 1.00
    +1   --->   0: N-127    1: W-  7    2: N- 12    3: W-  8    4: ?-???         nW: 1     Reliability: 1.00
    +1   --->   0: N-127    1: W-  7    2: N- 12    3: W-  9    4: ?-???         nW: 1     Reliability: 1.00
    +1   --->   0: N-127    1: W-  7    2: N- 12    3: W- 10    4: ?-???         nW: 1     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N-  1    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N-  2    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N-  3    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N-  4    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N-  5    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N-  6    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N-  7    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N-  8    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N-  9    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N- 10    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N- 11    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N- 12    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W- 10    2: N- 13    3: ?-???    4: ?-???         nW: 2     Reliability: 1.00
    +1   --->   0: N-127    1: W- 10    2: N- 13    3: W-  1    4: ?-???         nW: 2     Reliability: 1.00
    +1   --->   0: N-127    1: W- 10    2: N- 13    3: W-  2    4: ?-???         nW: 2     Reliability: 1.00
    +1   --->   0: N-127    1: W- 10    2: N- 13    3: W-  3    4: ?-???         nW: 2     Reliability: 1.00
    +1   --->   0: N-127    1: W- 10    2: N- 13    3: W-  4    4: ?-???         nW: 2     Reliability: 1.00
    +1   --->   0: N-127    1: W- 10    2: N- 13    3: W-  5    4: ?-???         nW: 2     Reliability: 1.00
    +1   --->   0: N-127    1: W- 10    2: N- 13    3: W-  6    4: ?-???         nW: 2     Reliability: 1.00
    +1   --->   0: N-127    1: W- 10    2: N- 13    3: W-  7    4: ?-???         nW: 2     Reliability: 1.00
    +1   --->   0: N-127    1: W- 10    2: N- 13    3: W-  8    4: ?-???         nW: 2     Reliability: 1.00
    +1   --->   0: N-127    1: W- 10    2: N- 13    3: W-  9    4: ?-???         nW: 2     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N-  1    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N-  2    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N-  3    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N-  4    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N-  5    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N-  6    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N-  7    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N-  8    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N-  9    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N- 10    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N- 11    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N- 12    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N- 13    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N- 14    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: W-  9    2: N- 15    3: ?-???    4: ?-???         nW: 3     Reliability: 1.00
    -1   --->   0: N-127    1: ?-???    2: ?-???    3: ?-???    4: ?-???         nW: 0     Reliability: 1.00
```

Fig.1.3 a triple whistle whithout imperfections

[See code: Counter.cpp]
[See code: Counter.h]