Coding with Knots

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Abstract

Abstract goes here

The Inca empire flourished at its height to 37 million people, without the need of money or a written language. We know that numeric information was stored by the Incas using *quipus*, a digital knot based recording system which was used in combination with black and white stones to read and calculate[]. Not many of them are extant, most were burned in the colonial wars. Until today, two thirds of the quipus discovered are untranslated, and do not fit into any known numeric coding system.

As a civilisation coming to terms with transitions to digital forms of social organisation, the Incas provide us with a useful counterpoint with which to understand our relationships with technology.

Much of the data contained within the Inca's knots are still completely unknown to archaeological research, and there may be value in bringing a cross-disciplinary approach, applying different visualisation and sonification methods to this problem. These methods, becoming attuned to what we try to convey with them, in turn may change the way we approach contemporary data.

The information available to us via the database of the Harvard Quipu Archive[1] is derived from a set of quipus encoded with information on thread type, knot type, knot position, colour and the currently understood base 10 numeric encodings.

Methods

How to approach something of which we only know for sure that it represents something, but something we don't know? Even more, where we don't know in what way it is represented? From reports we learn that quipus were reformulated in use — they were a dynamic medium, more like a chalkboard than a book; they were used to archive, to convey, and operate on information. Quipus are a "communication-based textile" [Sonja Andrew, Textile Semantics: Considering a Communication-based Reading of Textiles, Textile 6 (2008), no. 1, 32–65.] in a very literal sense. Resembling scripture, we still cannot take it as a given that they were read from left to right only.

The problem resembles that of the archeological reconstruction of *chaînes opératoires*: the ramified paths of actions that were performed in the production of paleolithic stone tools, paths which sometimes can be read out of the artefacts and the left-overs and traces of this process (Bleed 2001). Only that here, the resulting artefact, rather than merely a result, is meant to actively convey and compute information. Where the translation and computation practice is unknown, however, progress is difficult.

[1] The Harvard Quipu Archive is available at http://khipukamayuq.fas.harvard.edu/ (accessed 4th January 2017)

Figure 1: A Spanish illustration of a Khipukamayuq (knot maker/keeper)

Figure 2: A close up of a small quipu showing undecyphered changes in colour, material and twist.

For the time being, perhaps the best we can do is to superpose the left-overs of past methods with our own translational and computational practices, and hope for a heuristic widening of the horizon. In the following we briefly address one particular form of such a heuristic: in *modality* (image and sound) on the one hand, and in *temporality* (reading methods), on the other.

Visualisation

To get a first understanding of the types of structures present in a quipu, a simple parser for the data was constructed[] which then converted the data into a form readable by the common command line application Graphviz[]. This convenient way to automatically layout tree structures provided us with a schematic representation of the structure of the record, with knots and colours.

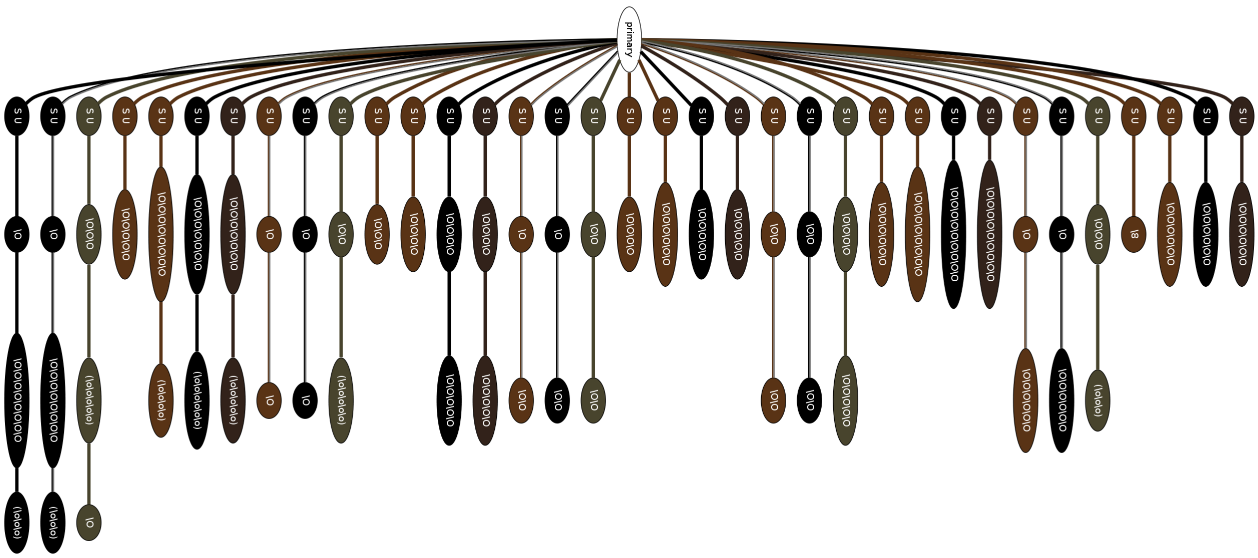


Figure 3: Quipu catalogued as #UR1138 rendered using Graphviz

The quipu cord colours are encoded in the database using Ascher colour codes (M. Ascher and Ascher 1978) which is an adapated form of ISCC-NBS colour coding, a standard provided by Judd and Kelly (2001). This was converted to hex RGB values required for the visualisation using an online tool.[2]

PixelQuipu

The visualisations produced with Graphviz are quite limited, as they tend to result in very large images, and don't provide enough control over how they are drawn. Also, topologically oriented displays are naturally limited where metrics are at stake. We needed to get more of an overview of the data, displaying the knots in the right positions with the pendants being the right length. A new system[], which we have named *pixelquipu*, was devised to display a quipu directly from the Harvard dataset:

[2]NBS/ISCC Color System http://tx4.us/nbs-iscc.htm, accessed 4th January 2017

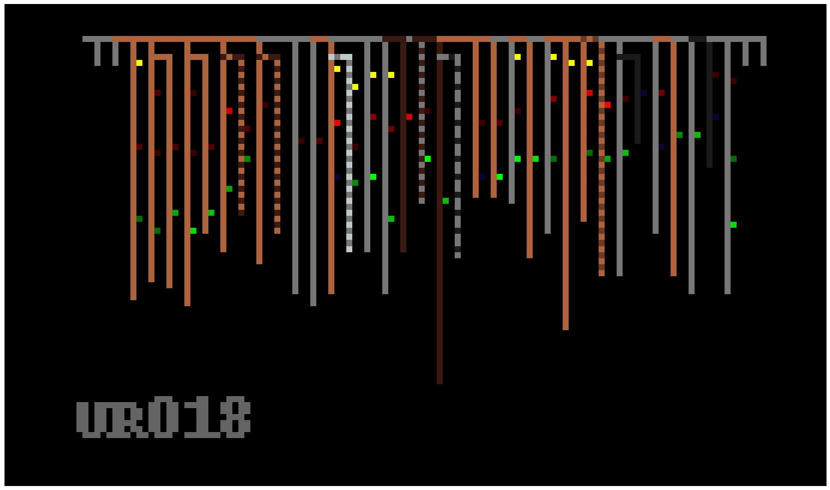


Figure 4: Quipu #UR018 rendered with PixelQuipu

Each knot is shown as a single pixel attached to the pendant, with a colour code of *red* as single knot, *green* for a long knot and *blue* as a figure of eight knot (*yellow* represents something unknown or missing). We are interested in the overall data rather than the specific values, so the value of the knot sets the brightness of the pixel. The colour variations for the pendants are represented, but there is no difference between twisted and alternating colours, also no twist direction is visualised.

Such a representation makes it easier to compare whole quipus, to compare their parts, to find reoccurring details and to shift focus from global to local structure.

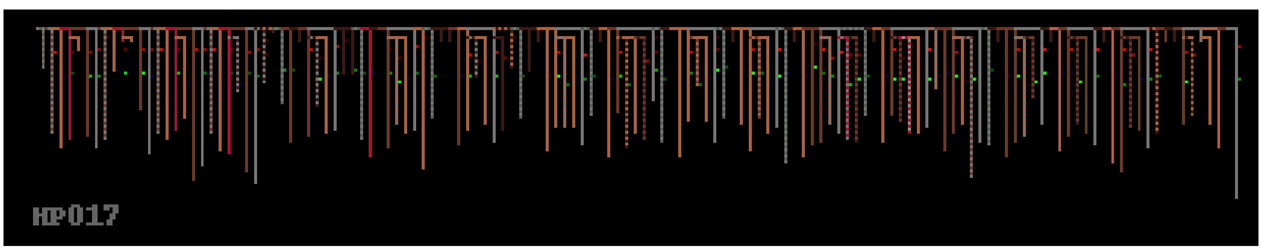


Figure 5: Quipu #HP017

We can now look at some quipus in more detail – what was the purpose of the red and grey striped pendants in the quipu below? They contain no knots, are they markers of some kind? This also seems to be a quipu where the knots do not follow the decimal coding pattern that we understand, they are mostly long knots of various values.

There also seems to be data stored in different kinds of structure in the same quipu – the collection of sub-pendants below in the left side presumably group data in a more hierarchical manner than the right side, which seems much more linear – and also a colour change emphasises this.

Read left to right, this long quipu below seems very much like you'd expect binary data to look – some kind of header information or preamble, followed by a repeating structure with local variation. The twelve groups of eight grey pendants seem redundant – were these meant to be filled in later? Did they represent something important without containing any knots?

The original idea of the pixelquipu was the attempt to fit all the quipus on a single page for viewing,

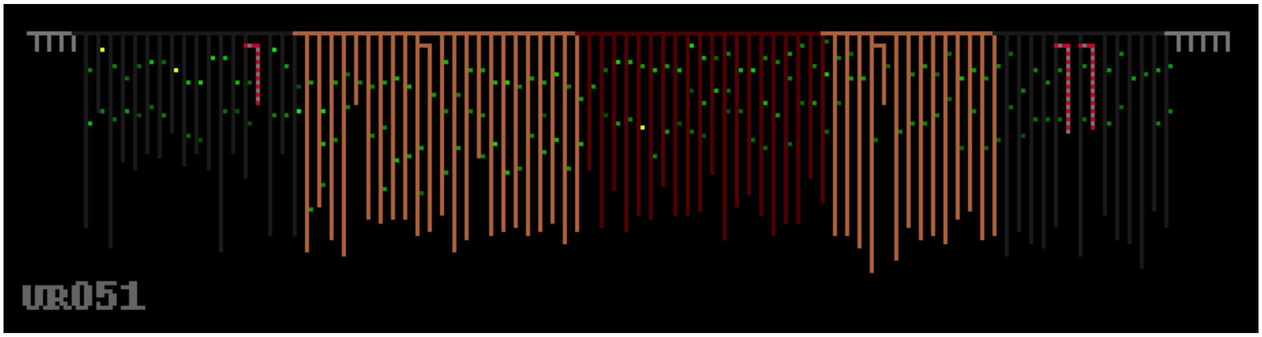


Figure 6: Quipu #UR051

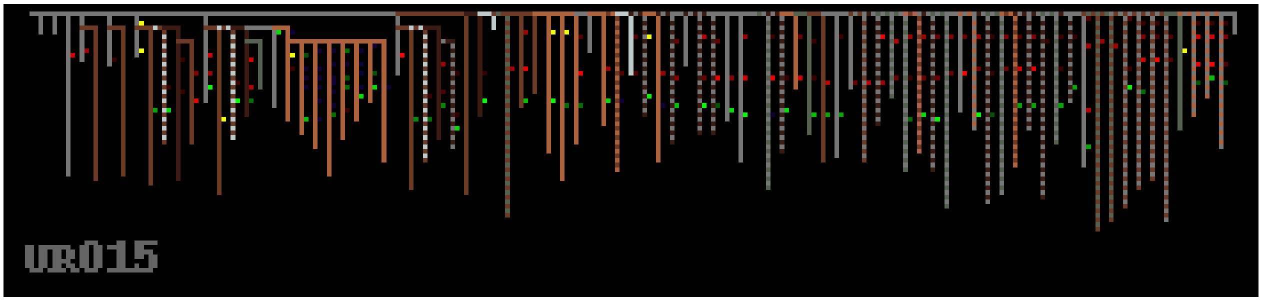


Figure 7: Quipu #UR015

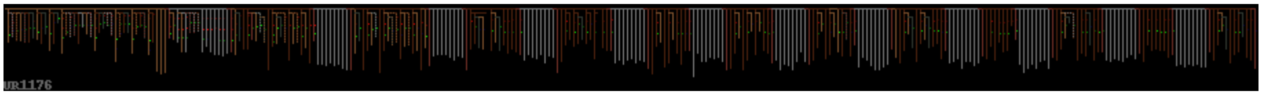


Figure 8: Quipu #UR1176

as it represents them with the absolute minimum pixels required. So finally, here are both pendant colour and entropy shown for all 247 quipu we have the data for:

Entropy

As we have so little idea what the Inca are telling us (or rather each other!) in their quipus, it seems appropriate to add a basic cryptanalysis approach to our toolkit of inquiry. One of the first things that a cryptanalyst will do when inspecting an unknown system is to visualise its entropy in order to get a handle on structures or patterns in the underlying information. The concepts of entropy differ very much in the different theories, and we should always keep in mind that the information concept itself depends on the theoretical context (see for instance Garfinkel and Rawls 2009 for a useful critique).

Here, for simplicity, we use entropy as [shannon and weaver] defined it: a measure of the *minimum* possible knowledge some set of data may convey. Entropy thereby describes how representation is bounded by specific laws of physics, ignoring the unknown specific coupling between operations in quipu use [“We require that a system of signals and a system of information be capable of being not only coupled but *variably* coupled in the sense that while this information would depend upon signal characteristics that it not be given in one-to-one fashion with signal characteristics. We require that it be possible to perform physical operations that will affect it while at the same time logical operations like matching, counting, comparing, classifying, measuring, be possible with it.”(ibid. p. 110)]

This graph shown in Figure xxx is calculated by making lists of all the discrete data of the same type, e.g. knot value, type, tying direction, pendant colours and ply direction (ignoring lengths and knot positions as these are continuous) – then calculating Shannon entropy on histograms for each one and adding them together.

We can also compare different types of information against one another, for example the main data we currently understand has some specific meaning are the knot values, partly derived from the knot type (long, single or figure of eight), which represent a decimal notation. If we compare the entropy of these we can expect them to have roughly similar average amounts of information:

The meanings of colours, ply and structure are largely unknown, but we can compare them with the knot values which we do understand. This could give an indication of whether they contain information. Here are the knot values compared with the colours:

And this is pendant ply direction compared with knot values for each quipu:

From this work we could see that the relationship to various data types is fairly uniform, and is not clustered in any way which would indicate different modes or categories of quipu. We can also use this technique to locate outliers to inspect further.

As well as looking at a quipu as a discrete unit, we can also look inside them and view their structure in terms of relative entropy. This is done below hierarchically, so a pendant’s entropy (shown as brightness) is that of its data plus all the sub-pendants, which seemed most appropriate given the non-linear form that the data take.

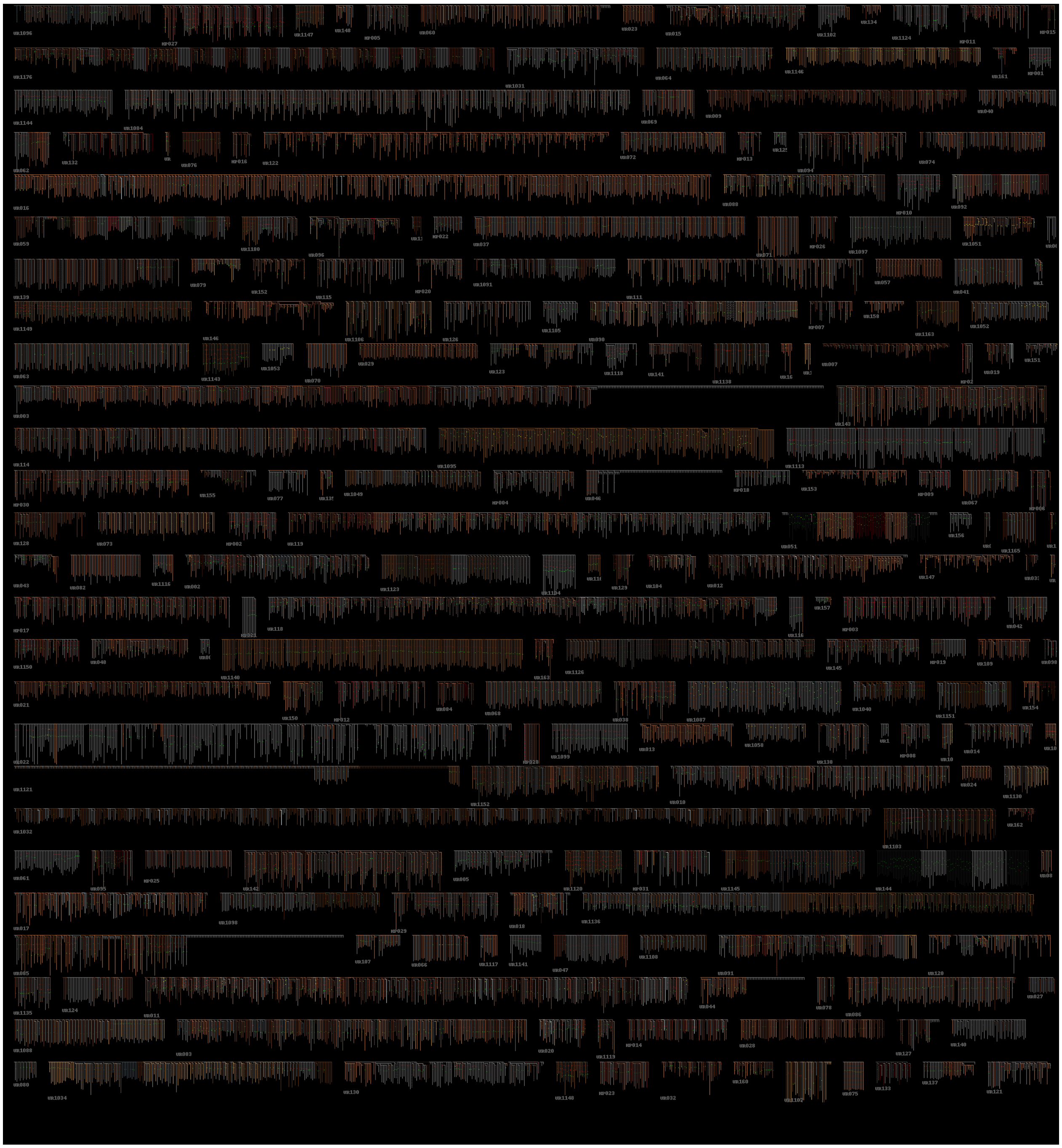


Figure 9: All 247 quipu in the collection

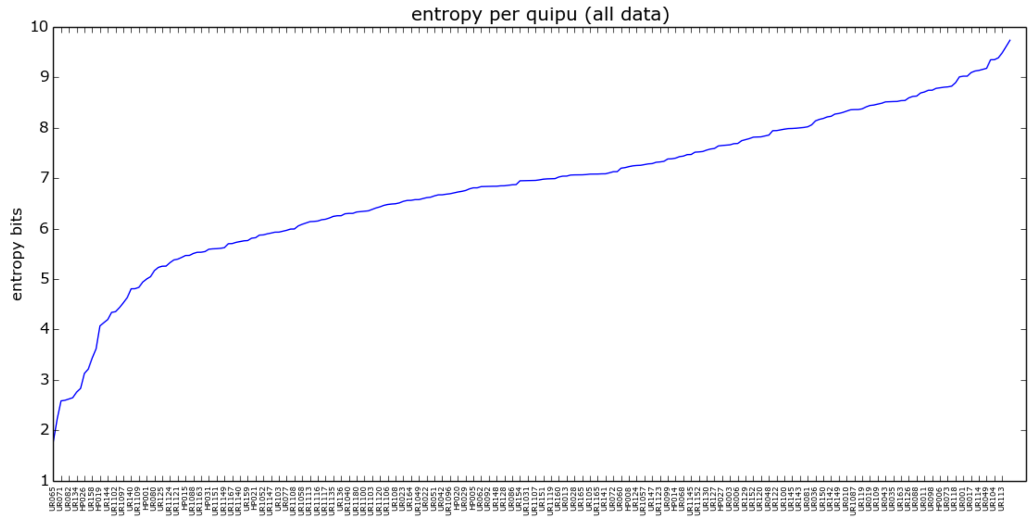


Figure 10: All the quipus in the Harvard database in order of average entropy bits they represent (only listing every other quipu ID)

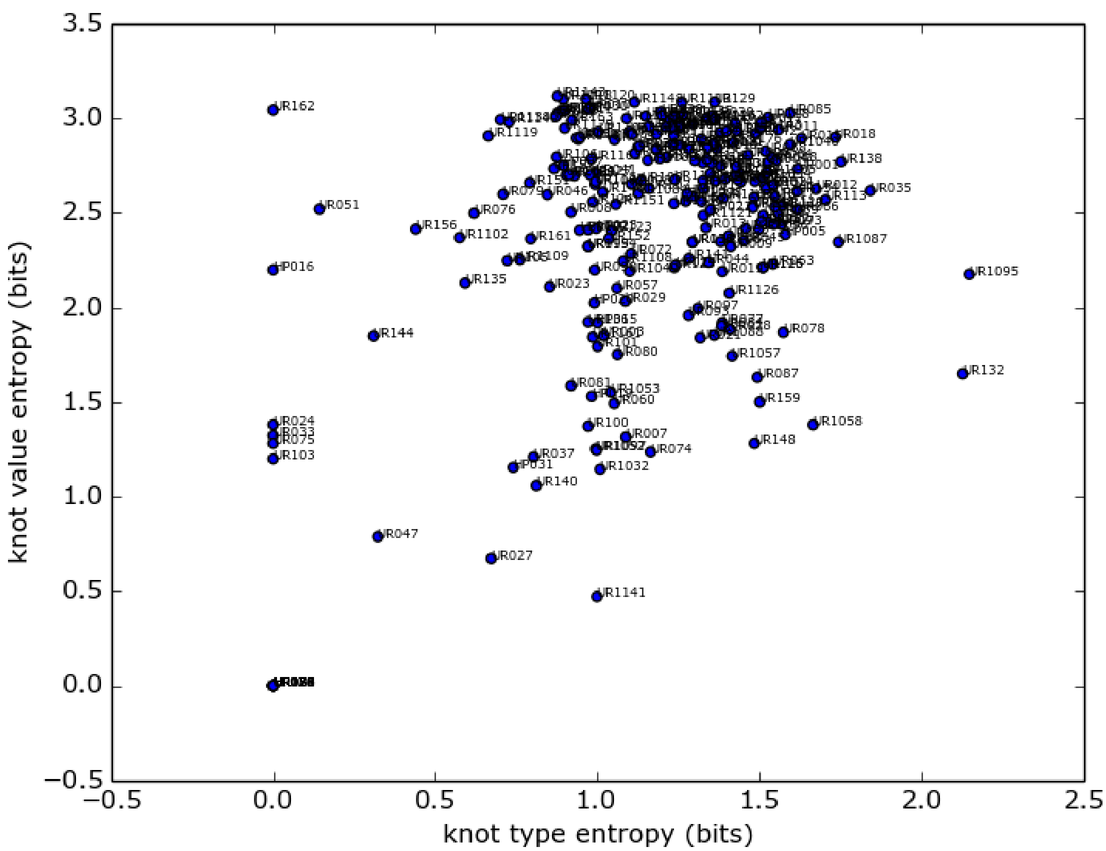
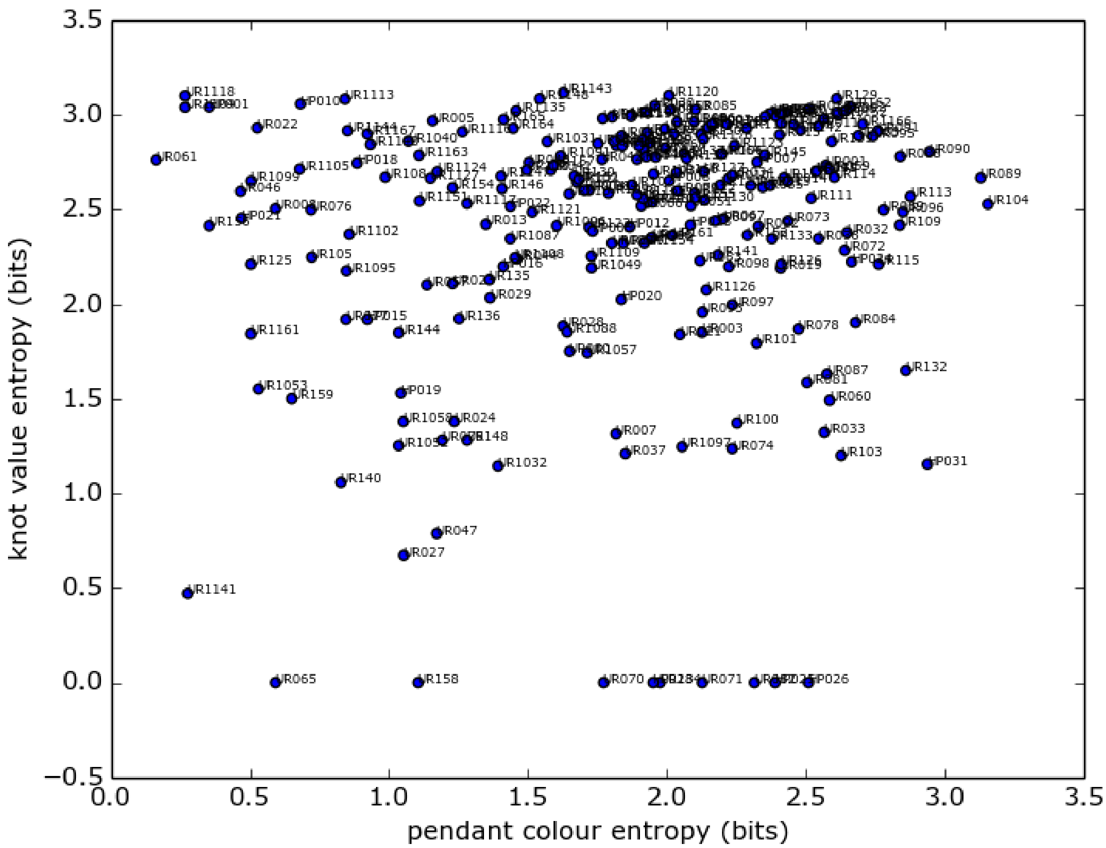


Figure 11:



knot value entropy (bits)
pendant colour entropy (bits)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
UR1118
UR1113
UR1143
UR1120
UR129
UR061
UR022
UR005
UR1040
UR1163
UR1105
UR1099
UR046
UR021
UR125
UR105
UR1095
UR1102
UR076
UR1161
UR144
UR136
UR1053
UR159
UP019
UR140
UR1058
UR024
UR1052
UR148
UR1032
UR047
UR027
UR1141
UR065
UR158
UR070
UR071
UP026
UR007
UR037
UR1097
UR074
UR100
UR033
UR103
UP031
UR132
UR087
UR060
UR101
UR078
UR084
UR097
UR003
UR1126
UP020
UR029
UR135
UR1049
UR1109
UR098
UR141
UR115
UR072
UR032
UR109
UR113
UR104
UR089
UR090
UR111
UR114
UR073
UR133
UR013
UR1087
UR1121
UR146
UR154
UR108
UR1124
UR1151
UR1031
UR085
UR145
UR1166
UR1057
UR1088
UR028
UR096
UR081
UP012
UR016
UP018
UR1135
UR164
UR1116
UR1167

Figure 12:

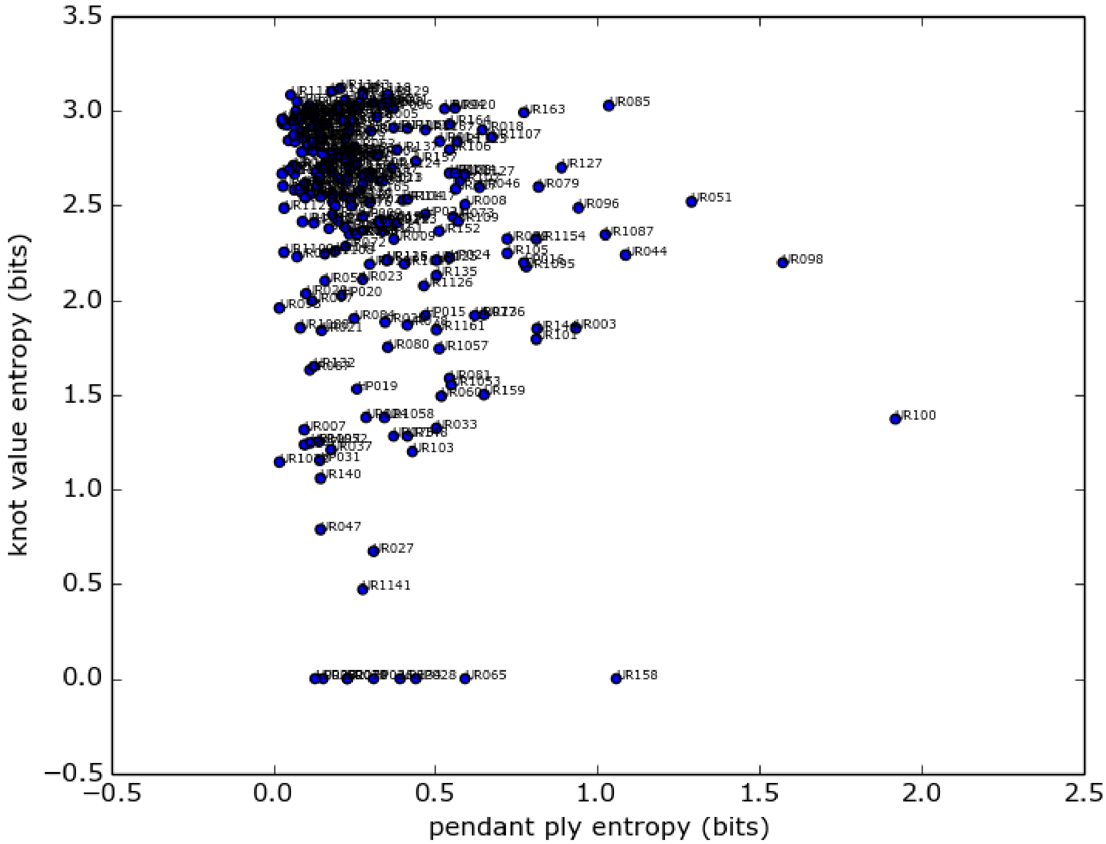


Figure 13:

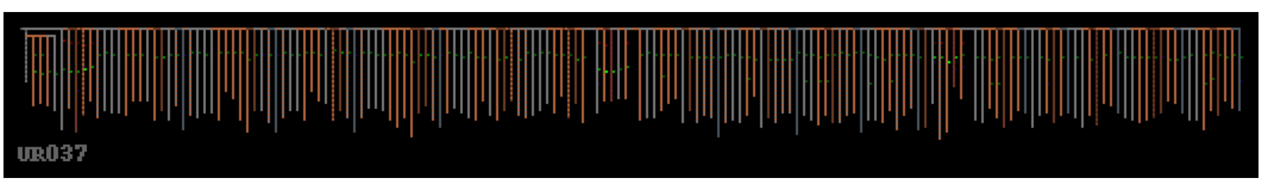


Figure 14:

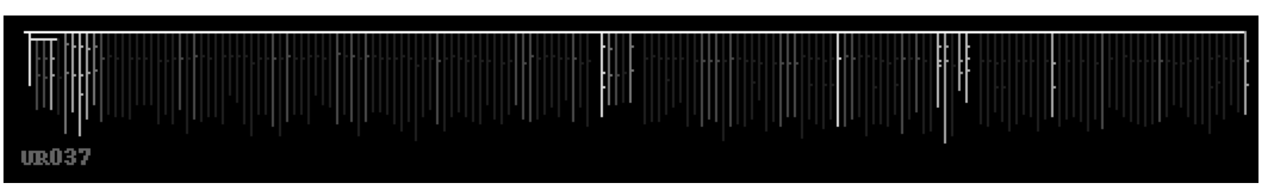


Figure 15:

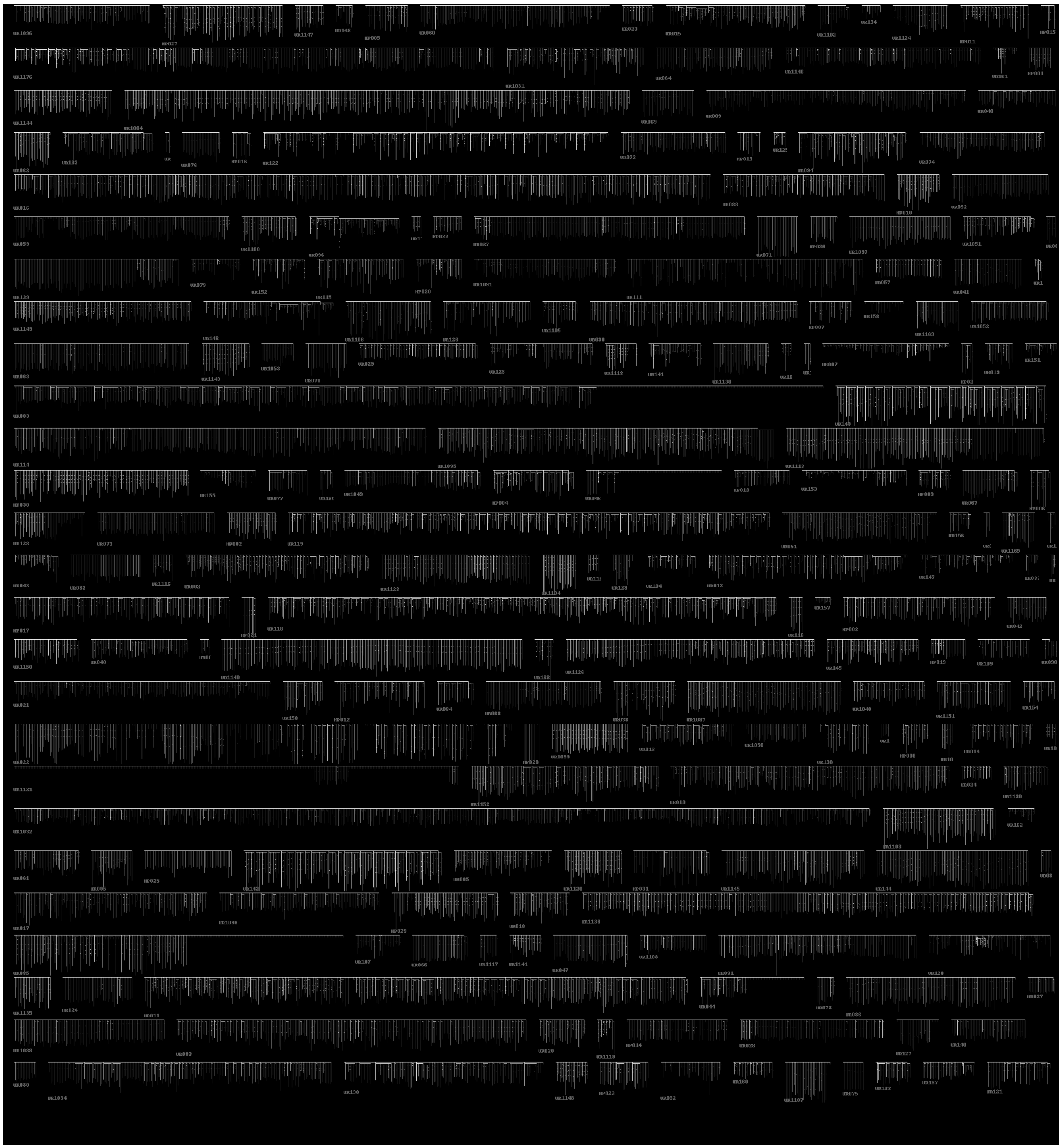


Figure 16: The local entropy for all the Quipu in the Harvard database.

Sonification

On the method

Where the significance of the structure of a specific medium is unknown, sonification can be a way to gain new insight. There are various reasons for this, which have partly to do with the way understanding is coupled with perception. Partly it is also due to the fact that listening takes a specific time and this is time we spend with absorbing a texture and its potential internal connections.

Visualisation offers the advantage of a very differentiated spatial distribution. By contrast, sonification is an excessively temporal method, which means that it can not only animate relationships, as one would do with a moving image, but everything is conveyed through oscillation. However, there are very many different sonification approaches in a sonification laboratory (Bovermann, Rohrhuber, and de Campo 2011) — which one to choose if we want to better understand quipus?

Our case presents specific challenges, because quipus are a branching structure, which, instead of just being laid out in space, has to be distributed in a time series. This obstacle has the positive effect that it broaches the tacit assumptions that remain hidden in pictorial representation: in fact we do not know how the quipus were read, so that the correct reading order is uncertain, and out of the many possible paths, many are non-trivial. Moreover, even reading orders that were not used by the Khipukamayuq (quipu-makers) may reveal important facts about what they encode.

The material qualities of quipus present us with the challenge of taking many levels of structured properties into account, including colours, knot positions, knot types, and ply. In our first experiments, we used sonification to juxtapose them in time.

Our experiments used the computer language SuperCollider, which in its abstraction level is optimal for the task at hand. Most of the program text can be changed at runtime, so that no graphical user interface precludes ideas of the researchers. The language is relatively well documented, and can be easily extended toward specific needs. A typical program in our system looks as follows:

```
// inka telefax
(
Tdef(\x, {
    ~traverse.(~data, { |x|
        var note = x[\colours] / 255 * 32;
        if(note.notEmpty, {
            (instrument: \sin, note: note, sustain: 0.1).play;
        });
        0.1.wait;
    })
}).play
)
```

In the following, we explain the motivations and outcomes of such scripts starting from a single dimension (here the sonification of thread colour) and the concurrent display of multiple dimensions.

Sonification experiments

Thread colour: a single dimension display

Quipus have a very distinct shape: a rather long series of small graphs, each of which has a couple of potentially relevant, but very different dimensions (such as color, number, length). Because sonification can give good insight into parallel serial data, our first sketch was to treat the series of pendants from one end of the primary cord to the next, as a series in time (as you would do with a text).

The current state of research makes it plausible that the colours used in quipus are of significance, but it is so far unclear of what. The shades of colours are subtle, as is their possible meaning. To start with, we sonified the colour pattern of the quipu #UR004 in a very simple way: a series of very short sine tone chords represent the red, green and blue components. The different colours of each pendant were thereby read like a musical chord:

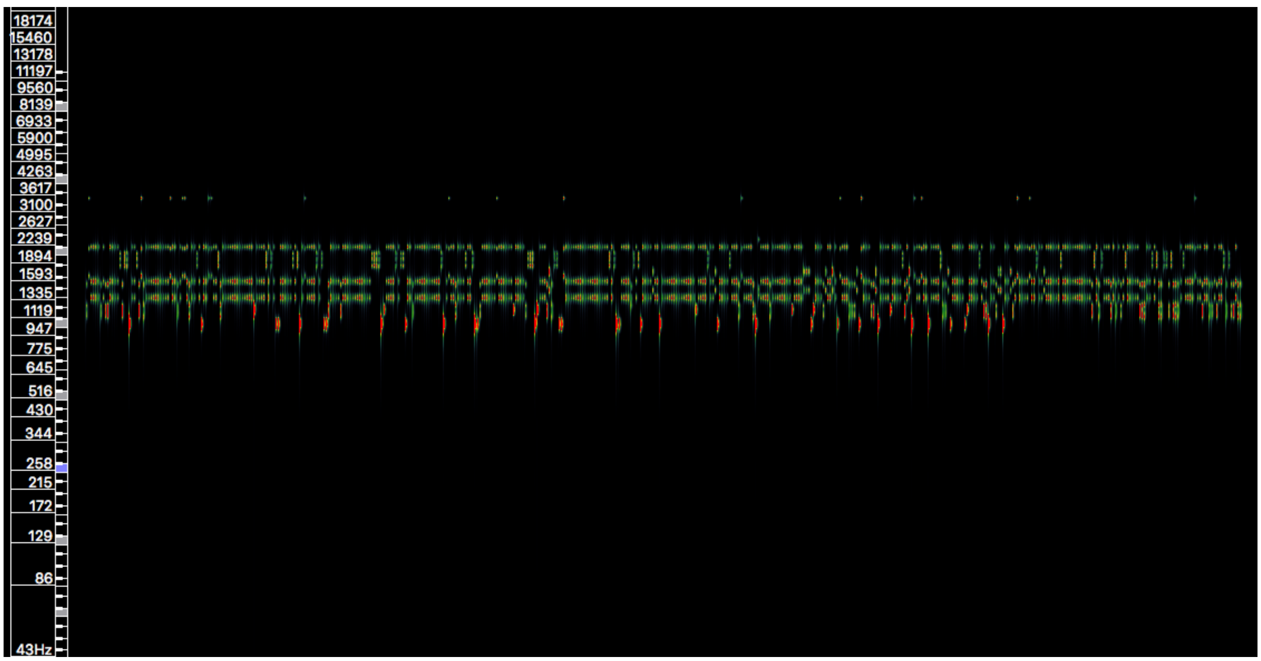


Figure 17:

This causes tones of grey to sound like a single tone, and the difference between components stands out as distance between separate partials. A rather simplistic sketch as it is, it nevertheless revealed a surprisingly rich rhythmic structure, which would be easy to overlook visually. This gave us some confidence that we should pursue this direction a little further.

Superposition: a multidimensional display

After an inquiry in the interpretations of archaeological findings, we found two promising quipus which made us curious. The paper by Juliana Martins[] on the astronomical analysis of an Inca Quipu pointed to two interesting candidates from Leymebamba (#UR006 and #UR009).

This time, we sonically displayed more of the data dimensions. Here is a first result (#UR006):

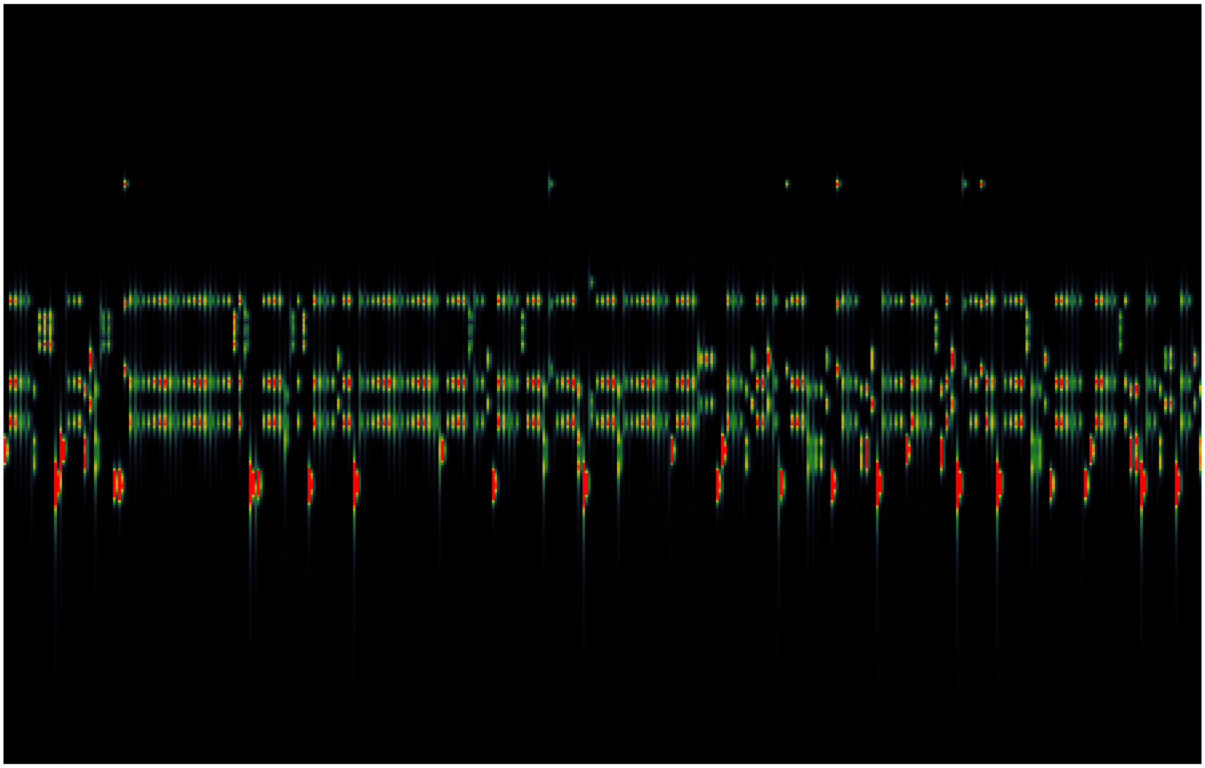


Figure 18:

It is not well visible in the spectrogram but audible that each short sound event (about 1/10 of a second shorter as we go down the subsidiaries) has a number of independent timbral properties, some of which have significant pattern across longer sections.

Table 1: An overview of which 'quipu dimension' is mapped onto which sound dimension.

quipu	sound
colour	sine tone spectrum of three partials

quipu	sound
branching level	duration between sound grains (inter onset duration)
pendant length	duration of each sound grain (relative to inter onset time)
pendant attach (verso or recto)	pan position left or right channel

quipu	sound
pendant ply (S or Z)	envelope shape (audible as "inversion effect")
unknown values	are usually interpreted as neutral (pan) or low (colour)

The moments of audible acceleration result from areas with many pendants that have subsidiaries (side branches). In various dimensions rhythmic patterns appear, which partly coincide and partly remain independent. Also, in some moments, we can hear sudden changes of the overall pattern, indicating a transition into a different logic.

You can see how the multidimensional display is a relatively straightforward extension of the single dimension one.

```
(
Tdef(\x, {
    var pani = ('R':-1, 'V':1, 'U':0);
    var plyi = ('S': 0, 'Z': 1, 'U': 0.5);
    ~traverse.(~data, { |x, level|
        var colours = x[\colours], note, pan, len, ply;
        var dur = 1/2 ** (level - 1) / 10;
        if(colours.notEmpty, {
            pan = pani[x[\pendant_attach]];
            ply = plyi[x[\pendant_ply]];
            len = x[\pendant_length] ? 25 / 25;
```

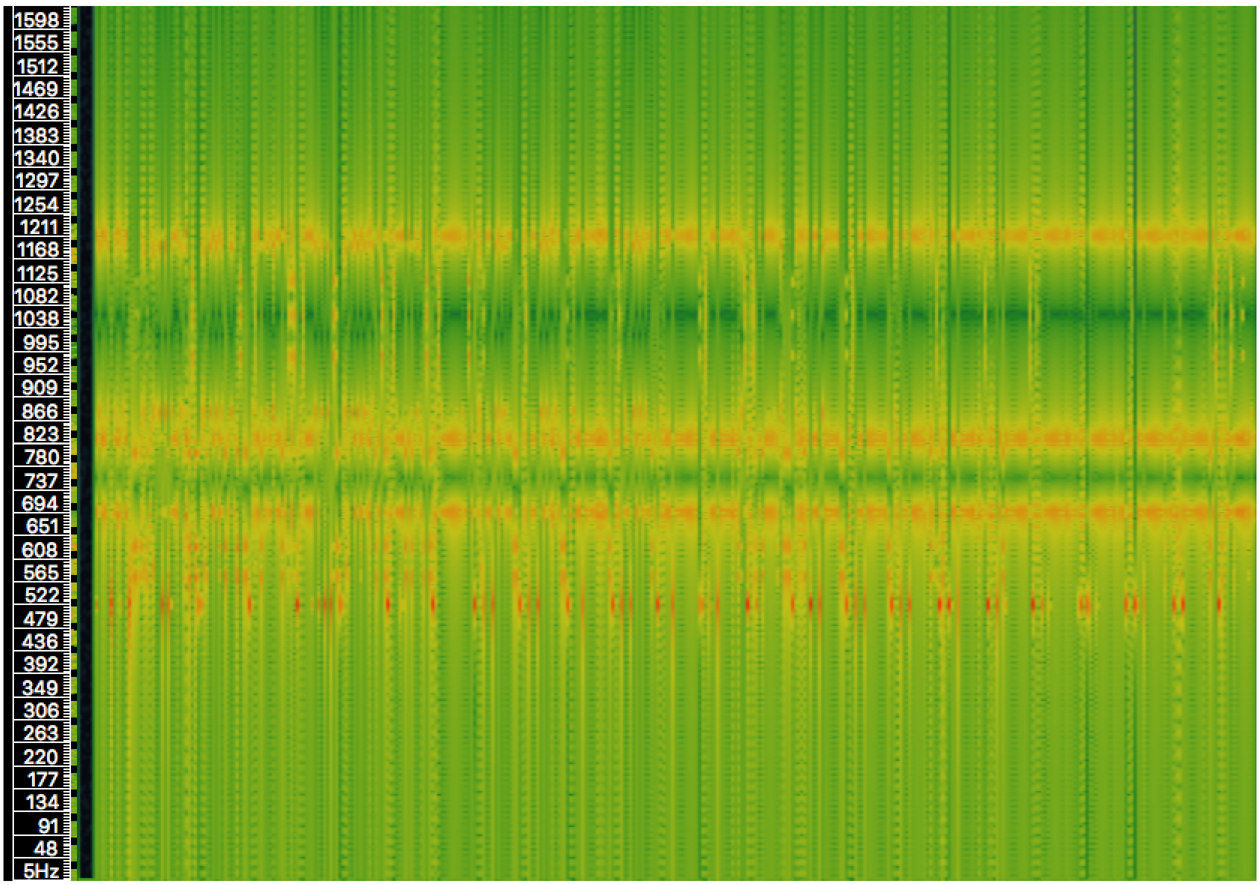

1598
1555
1512
1469
1426
1383
1340
1297
1254
1211
1168
1125
1082
1038
995
952
909
866
823
780
737
694
651
608
565
522
479
436
392
349
306
263
220
177
134
91
48
5Hz

Figure 19:

```
            note = x[\colours] / 255 * 36 + 12;
            (
                note: note,
                dur: dur,
                instrument: \sin,
                amp: 0.1/3,
                pan: pan,
                legato:len * 1.5,
                ply: ply
            ).play;
        });
        dur.wait;
    })
}).play
)
```

Knot-Spectra

So far we have considered only the properties of the pendants themselves, which certainly stand out less than the more obvious knots which were tied in them. Some of the knot patterns have been interpreted as numerical records in a decimal base encoding. The counter check of reading them as additions (like on an abacus) is consistent, and where such calculations have been found, the Harvard data set contains the numerical interpretation as a value. There are many quipus, however, which do not fall into this category. Here knots most probably are of significance, but we lack a matching interpretation. The attributes are: position, value, type (single, long, eight, or undefined), and spin.

We know from the numerical quipus that the place on the pendant is of significance, so that it makes sense to acoustically display this information. The following example is one from our experiments, where the known numerical value is interpreted as node (zero if not available), and is superposed with the spectral distribution derived from the position pattern. The spin is used as a pan position in the stereo field (left/right/center):

```
(
Tdef(\x, {
    ~traverse.(~data, { |x, level|
        var knots = x[\knots];
        knots.do { |k|
            var note, pan;
            note = k[\value];
            pan = k[\spin];
            (
        note:note,
        harmonic: k[\position],
        sustain: 0.01,
        instrument: \sin,
        sustain: 0.4,
        pan: pan
```

```
      ).play;
        };
        0.1.wait;
    })
}).play
)
```

For another variant in sonifying the knot data, we used the multichannel sound system available in the experimental laboratory in Robert Schumann Hochschule Düsseldorf. The program code demonstrates that very little modification is necessary to use the spectral information as an offset into the eight channels:

```
(
Tdef(\x, {
  ~traverse.(~data, { |x, level|
      var knots = x[\knots];
      knots.do { |k|
          var note, pan;
          note = k[\value];
          pan = k[\spin];
          (
        note:note,
        out: k[\position] * (8 / 20),
        sustain: 0.01,
        instrument: \sin,
        sustain: 0.4,
        pan: pan
      ).play;
      };
      0.1.wait;
  })
}).play
)
```

The Project "Inka Telefax. Listening to Precolumbian Administration without understanding a word"

Conclusions

Weaving in the broadest sense of the term covers an intermediate space between what has been called "form and function". Form usually being that of non-functional representation or decoration, function usually that of non-formal use for specific practical purposes. These terms are misplaced, as it is commonly acknowledged, because decorative and iconic detail at least has a social function (see also Andrew 2008). Quipus are a specific case, however, because here, the decorative detail serves a representative function, mostly, but perhaps not exclusively, an administrative one. Because of the small number of extant artefacts, their retrospective decoding becomes a difficult task; at the same time, all measurable information about them has been translated to the predominant administrative tool of our culture, Excel spreadsheets.

Our basic cryptanalysis gives us a comparison between different quipus, and shows that the differences between them are fairly continuous - our entropy analyis has not revealed easily determined categories of quipu in the corpus in the dimensions that we compared. This may be surprising given that different Khipukamayuq may have employed different techniques, and that these may have evolved over time or distance. On the other hand, when we measure discontinuities of potential data storage within the quipus — we find areas of complexity along with areas of low information, further analysis may help to understand structural patterns. By proposing some experimental "laboratory methods" [ref] for the sonification of those data sets, we hope to have broadened the perspective of their reading.

Listening to the inner structure of these artefacts is a method of systematic spreading of awareness over time. Unlike an image which can be read in any order, a sonification aligns the reading direction, while keeping undecided what is being listened to. Sound thereby has very different affordances than the common descriptive, diagrammatic and numerical methods. Used by artists and composers, such sonifications can cultivate a movement between archeological interest and aesthetic sensibility. Used by archeologists as a methodological alternative, it might lead to new ideas of how to read quipus in their cultural context.

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