TITLE
Quipus, computation and generative grammars

Topic:
Generative art, computation, history

Author(s):
Umberto Roncoroni
Perú, Universidad de Lima, Faculty of Communication

Abstract
Quipus are systems of cables and knots of different forms and colours used hundreds of years ago by prehispanic Peruvian cultures as information systems, data storage and to perform some kind of mathematical operations. Some authors also consider the *quipu* as a writing systems, used to register poems and important social and military events.
Quipus have been widely studied, but how they exactly work is not completely understood.
One of the most important essays about *quipus* is Raimondo di Sangro's *Lettera Apologetica*, published in Naples in 1784. Based on contemporary evidences and historical documents, this book is an interesting hypothetical interpretation of *quipus* as computation and writing.
But this work does not receive, in digital art and computer science, the interest it deserves. Its generative potential is still undiscovered, even if the research of di Sangro do offer interesting historical knowledge on computational processes, such as data structures, and original insights on writing and generative grammars. The 17th century Italian syntaxes and the baroque literary style of di Sangro certainly jeopardize the comprehension and evaluation of his theories.
So far, the goal of this paper is, in the first place, to present, in a clear and schematic way, the interpretation of *quipus* of this Neapolitan alchemist and inventor in the scope of generative art and generative grammars; in the second place, to test and verify its linguistic and computational capabilities, compared with other writing systems of ancient Peru, like *tokapus* and knot textiles.
First, I will explain what *quipus* are, considering state of the art new research on the topic. Then I will analyse and explain Raimondo di Sangro's hypothesis. Third, I will show how his ideas could be used to refine some generative processes and how *quipus* could be used to inspire digital creativity. Finally, I will present, as hypothesis for future research, examples of hypothetical computational techniques based on di Sangro's *quipus*.
This paper can provide scholars, programmers and generative artists some valuable historical references and material for future research.

hroncoro@ulima.edu.pe

Key words: quipus, generative grammars, computation, history

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Quipus, computation and generative grammars

Dr. Umberto Roncoroni Osio
Universidad de Lima, Lima, Perú.
www.digitalpoiesis.org
e-mail: hroncoro@ulima.edu.pe

Abstract
Quipus are collections of ropes with knots of different forms and colours used by pre-Hispanic Peruvian cultures as information systems, data storage devices and to perform mathematical operations. *Quipus* have been widely studied, and some scholars even consider *quipus* writing systems, capable of recording poems or social events. Nevertheless, we still do not know for sure how they were operated. In this sense, one of the most important essays about *quipus* is Raimondo di Sangro's *Lettera Apologetica*, published in Naples in 1784. Based on contemporary evidences and documents, this book is an interesting hypothetical interpretation of *quipus* that does not receive, in computer science and generative art, the interest it deserves, even if it clearly offers original insights on computational processes, data structures and generative grammars. So far, the goal of this paper is, in the first place, to present, in a clear and schematic way, the interpretation of *quipus* of this Neapolitan alchemist and inventor in the scope of generative art; in the second place, to test and verify its linguistic and computational capabilities. First, considering the state of the art research on the topic, I will describe what *quipus* are. Then I will explain and evaluate Raimondo di Sangro's hypothesis. Third, I will show how *quipus* could be compared to modern computational techniques and data structures. Finally, I will suggest creative recursive generative processes based on di Sangro's linguistic application of *quipus*. The conclusions of this paper can provide scholars, programmers and generative artists not only with some valuable historical references and material for future research, but also with some new creative approaches to generative art.

Introduction
The importance of cultural traditions in information technologies and computer science is often underestimated. Programmers are focused on practical problems (efficiency, speed, reliability, etc.) of digital media, while social sciences scholars consider only its impact overlooking the cognitive influence of computational processes (algorithms and interfaces) on the users.
However, considering the complex structure of software, it should be obvious that digital applications are culturally biased on philosophical, scientific and historical facts. Software are *texts*, in the sense defined by Barthes [9] and *archi-writing* in the sense of Derrida [1]. For instance, reckoning its empiricist and positivist roots, computer science is clearly an Anglo-Saxon heritage [7].
Such cultural values outline the form of computational processes, algorithms and interface designs globally distributed by internet. The outskirts of technological development (like Peru) suffer a sort of new colonialism and we can safely speak of silencing the subaltern [15]. The consequence of all this is digital divide, in other words, that possible contributions to digital media are limited by these biases and that a huge capital of knowledge is left behind [3, 4]. Digital technology is a double–edged weapon.
For these reasons, it is paramount to evaluate the links between cultural traditions, computation and digital divide. Not in the sense that cultural traditions are barriers to digital technology development, but because development should be culturally sustainable and stimulated by the

tradition itself. One interesting topic here is the computational value of pre-Columbian artefacts. *Quipus*, which use spread all over the Andes from Ecuador to Chile, are an excellent case of study.
Thus, this paper has two goals. First, to resume, in a clear and schematic way, the interpretation of *quipus* of the Neapolitan alchemist and inventor Raimondo di Sangro, prince of San Severo [5]. In the second place, to test and verify its linguistic and computational capabilities, an option sustained by other writing systems of ancient Peru, like *tokapus* and knot textiles [10, 17].The knowledge we can acquire from *Lettera apologetica* is, as I hope to prove, of the greatest interest for generative art and shape grammars.
To succeed, I will start explaining what *quipus* are, considering state of the art new research on the topic. Then I will analyse and discuss Raimondo di Sangro's hypothesis about *quipus* as writing systems. Finally, I will show how his ideas and *quipus* could inspire digital creativity and refine generative processes, such as generative grammars and L-Systems.

Quipus

Quipus are collections of wool ropes with knots of different shapes and colours, sequentially joined along a main cable. A *quipu* could hold even hundreds of knots sequences, forming huge artefacts of many pounds of weight. Prince di Sangro's analysis of *quipus* is the first attempt to understand these ancient Peruvian artefacts and still is the main reference for contemporary research (8, 13).



Fig. 1a: Quipu. (https://hidraulicainca.com). Fig. 1b: Quipu. (http://www.torontohispano.com)

His interpretation was grounded upon Blas Valera and Poma de Ayala original documents[13] and, even if the real usage of *quipus* is not completely understood, it is obvious that these knotted ropes were used by public administrators as computational systems to register agricultural production data and commercial transactions.

[13] Blas Valera Pérez (1545 - 1597) was a priest, scholar and historian. Felipe Huamán Poma de Ayala (1534 - 1615), was a peruvian chronicler during the Virreinato.

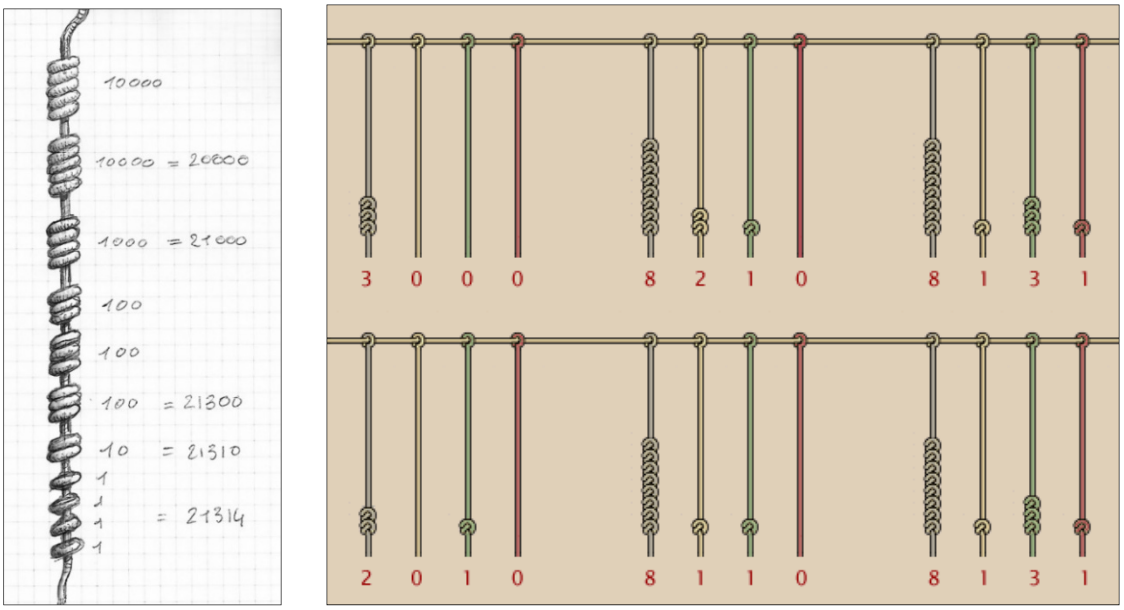

Fig. 2a. Copy by the author of the original di Sangro's illustration, explaining the record of the number 2314. Fig. 2b. Actual interpretation (Urton, 2014). The position of each knot represents the index, and the number of knots represents the numerical value.

However, following the primordial work of di Sangro, scholars generally accept not only that *quipus* were information systems, but also that these artefacts were a sort of writing system to register historical events and poems [2, 6, 8, 12][14].
Anyway, the field is open to further research. My contribution here is to expound di Sangro's interpretation (since the original text is quite difficult to understand and no translations are available) and to suggest how his theories could be used to experiment new generative techniques and algorithms.

The Lettera Apologetica: data and words

The most interesting part of di Sangro's work is his hypothesis of *quipus* as writing systems and the analysis of their linguistic advantages. It is important to reckon that the book of di Sangro is not a scientific research, but part an imaginary interpretation of contemporary evidences and part a work of fantasy and linguistic creativity. He even thought that *quipus* could be a better way to encode numbers and letters than our Latin and Arabic notations[15].
Ancient Peruvians possibly wrote words and sentences, following di Sangro, using a set of primary words (axioms, in L-Systems' jargon)[16] to generate new words, using primary words' specific set of syllables. Special icons or ornaments, like golden disks, small painted arcs and other jewelry designs, inserted at the beginning of the knots' string (fig. 3), identified each primary words and made possible the identification of the correct set of syllables and finally, the correct understanding of the new word.

[14] "*In 2015, I examined two khipus preserved by village authorities in Peru. Villagers state that these sacred khipus are narratives epistles about warfare. Analysis reveals that the khipus contain 95 different symbols, a quantity within the range of logo syllabic writing*" [6]. This cite makes reference to the *quipus* of Collata, probably written by local leaders during the rebellion of Inka Yupanki in 1783.
[15] We must consider that science still was intertwined with magic, alchemy, and superstition. Anyway, there is evidence in a book of Blás Valera, who reported an ancient poem wrote in *quipus*.
[16] In the sense that the noun axiom has in generative grammars, shape grammars and L-Systems, say, the starting symbol or symbols from which the substitution process begins.

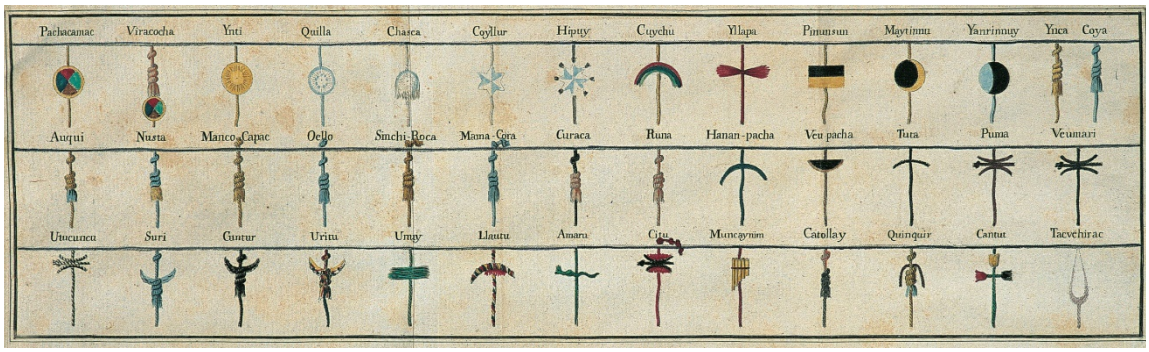

Fig. 3. Original illustration of di Sangro, showing primary words and their icons.

In figure 4 I made a map of the primary words (the axioms) imagined by di Sangro, and example of how new words could be formed using the syllables extracted from these primary words.

	PRIMARY WORDS	MEANING	SYLLABLES				#
1	PACHACAMAC	God, creator of universe	PA	CHA	CA	MAC	4
2	VIRACOCHA	God, human form	VI	RA	CO	CHA	3
3	YNTI	Sun	YN	TI			2
4	QUILLA	Moon	QUI	LLA			2
5	CHASCA	Venus	CHA	SCA			1
6	COYLLUR	Star	COY	LLUR			2
7	HIPUY	Comet	HI	PUY			2
8	CUYCHU	Rainbow	CUY	CHU			2
9	YLLAPA	Ray	YLLA	PA			1
10	PINUNSUN	Equinox	PI	NUN	SUN		3
11	MAYTIÑU	Sun eclipse	MAY	TI	ÑU		3
12	YANRIÑUY	Moon eclipse	YAN	RI	ÑUY		3
13	YNCA	King	YN	CA			1
14	COYA	Queen	COY	YA			2
15	AUQUI	Prince	AU	QUI			2
16	NUSTA	Princess	UN	STA			2
17	MANCO CAPAC	First Inca	MAN	CO	CA	PAC	3
18	OELLO	First Queen	OE	LLO			2
19	SINCHI ROCA	Second Inca	SIN	CHI	RO	CA	3
20	MAMA CORA	Second Queen	MA	MA	CO	RA	2
21	CURACA	Feudatory, noble	CU	RA	CA		1
22	RUNA	Man	RU	NA			2
23	HANAN PACHA	Sky	HA	NAN	PA	CHA	2
24	VEU PACHA	Hell	VEU	PA	CHA		1
25	TUTA	Night	TU	TA			2
26	PUMA	Lion	PU	MA			1
27	VEUMARI	Bear	VEU	MA	RI		0
28	UTUTUNCU	Tiger, (jaguar, otorongo)	U	TU	TUN	CU	2
29	SURI	Ostrich	SU	RI			1
30	CUNTUR	Condor	CUN	TUR			2
31	URITU	Parrot	U	RI	TUN		0
32	UNUY	Water	U	NUY			1
33	LLAUTU	Colored braid	LLA	U	TUN		0
34	AMARU	Snake	A	MA	RU		2
35	CITU	Sun honoring	CI	TU			1
36	MUNCAYNIM	Pan flute	MUN	CAY	NIM		3
37	CATOLLAY	Duel	CA	TO	LLAY		2
38	QUINQUIR	Student dress	QUIN	QUIR			2
39	CANTUT	Cantuta, flower	CAN	TUT			2
40	TACVEHIRAC	Sling	TAC	VE	HI	RAC	4
						TOT. SILABAS	76

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PRIMARY WORDS	SYLLABLES			
CURACA	CU	RA	CA	
PACHACAMAC	PA	CHA	CA	MAC
NUSTA				

CU MAC NUSTA

CATOLLAY	CA	TO	LLAY	
MAMA CORA	MA	MA	CO	RA
QUINQUIR	QUIN	QUIR		

TORALLAY QUIN

HIPUY	HI	PUY		
YANRIÑUY	YAN	RI	ÑUY	
QUILLA	QUI	LLA		
TUTA	TU	TA		

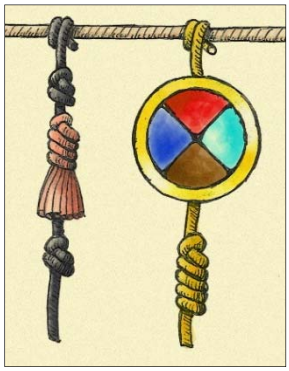
PUYÑUY QUITA

YLLAPA	YLLA	PA		
QUINQUIR	QUIN	QUIR		
CURACA	CU	RA	CA	
YANRIÑUY	YAN	RI	ÑUY	

PAQUIR CAYAN

Fig.4 Primary words, English meaning, syllables and part of the poem studied by di Sangro.

To write a word, first the writer must insert the symbol of the primary word. Then he must identify which portion (syllable) of the primary word will be used. For example, the primary word could be ***PACHACAMAC,*** represented by di Sangro with a golden disk divided into four sectors of different colors (fig. 3, 5a). To do this, the writer must insert a knot which form corresponds to the position of the syllable in the primary word: a simple knot for the first part/syllable, double knots for the second part, etc., as shown in fig. 5b.



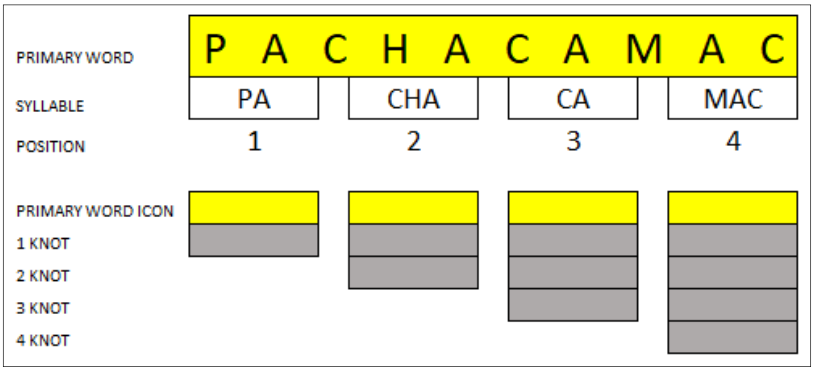


Fig. 5a. The designs of the primary words CURACA and PACHACAMAC (illustration of the author from the original of RdS). Fig 5b. Scheme of knots and syllable positions of the word PACHACAMAC.

Now, to form a new word, for example the word ***CUMAC*** as in di Sangro's example (fig. 4), you must use the firs part of the primary word ***CURACA***, and the fourth part of the primary word ***PACHACAMAC***.

Note that this literary interpretation of *quipus*, most an invention of di Sangro, certainly was the first attempt to find its meaning and practical usage in contemporary culture.

Quipus and alphabets

In this paragraph, I will explain how di Sangro encoded letters and numbers, using the knot system of the *quipus*, for the construction of new words and complete utterances in Italian or others European idioms. This is absolutely a product of the fantasy and creativity of our Neapolitan prince, it is not how *quipus* were used, but here we find the most interesting contribution to generative linguistic models.

The first problem is how to encode the vowels. Di Sangro's solution is to use a knot of a specific color for each vowel. He suggested to choose a color which name first letter corresponds (more or less, I should say) to the vowel, considering that the language of reference is Italian:

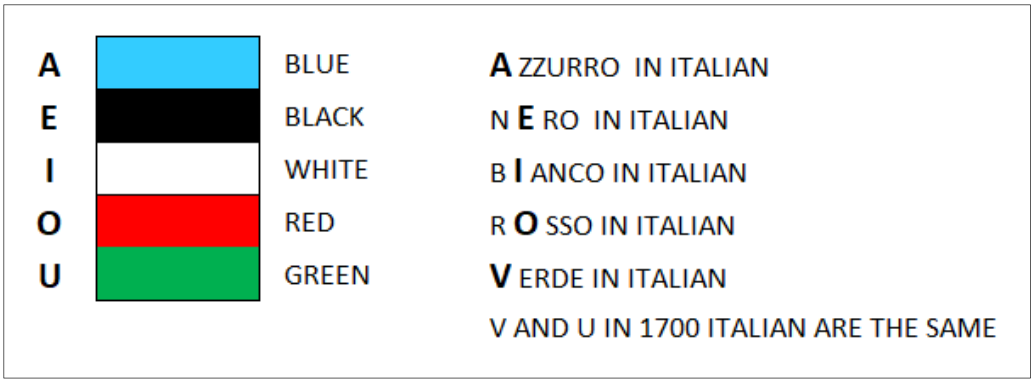
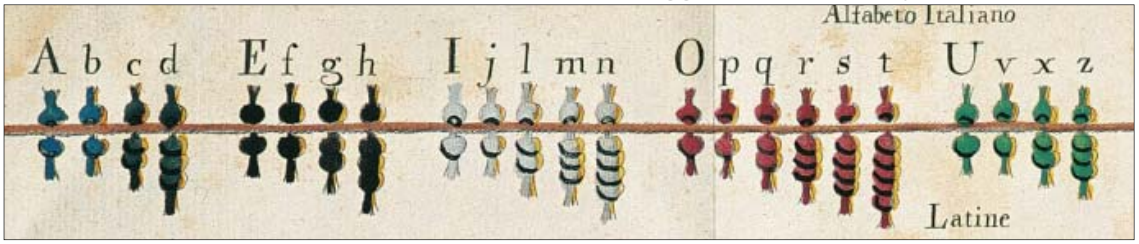


Fig. 6. Map of the match of colors, colors names and vowels.

On the other hand, consonants are identified and mapped using vowels as reference. Consonants, in other words, are grouped following their precedent vowel: "b,c,d" follow the vocal "a", "f,g,h" the vowel "e", and so on. The vowel that begins the consonant series is called the dominant. So "a" is the dominant of "b,c,d". Consonants are also represented with knots, which number depends

from its distance from the dominant vowel (the bigger the farer they are from the dominant).



Dominant		Consonants	Distance from the vocal
a	>>	**b c d**	(b) **1** (c) **2** (d) **3**
e	>>	**f g h**	(f) **1** (g) **2** (h) **3**
i	>>	**l m n**	(l) **1** (m) **2** (n) **3**
o	>>	**p q r s t**	(p) **1** (q) **2** (r) **3** (s) **4** (t) **5**
u	>>	**v x z**	(v) **1** (x) **2** (z) **3**

Fig. 7a. Scan of Raimondo di Sangros' original illustration. Fig.7b table of vowel-consonants.

Consonants' colors are the same of their dominants, but, to avoid confusion between them, the string of the knots of the consonants should be crafted using a string of the color of the dominant plus a yellow string (yellow also represents the color of empty space between letters or words). The following illustration is an example of a word using di Sangro's method:

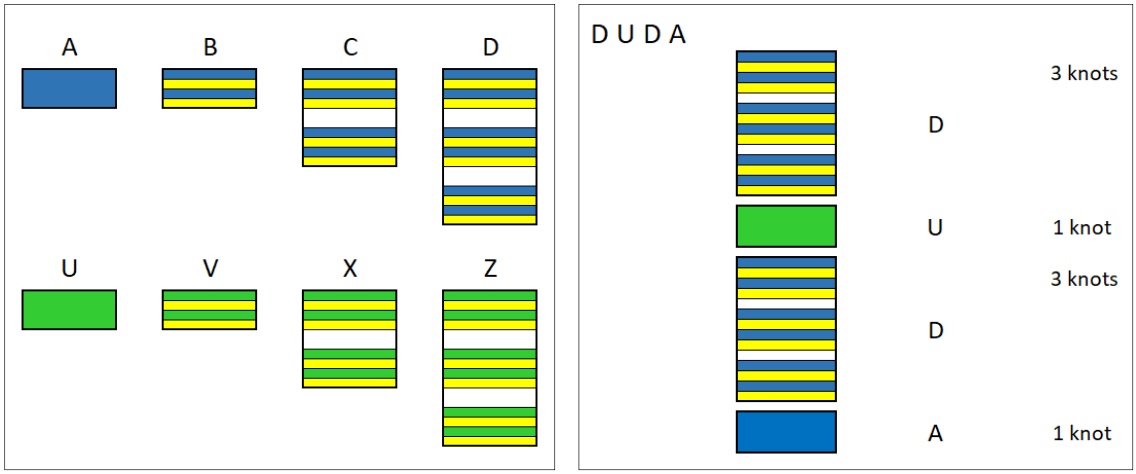


Fig. 8. Map of the consonants representation and a sample word (DUDA, meaning doubt) using the system of di Sangro.

Quipus, memory palaces and data structures

After this, I will try to test di Sangro's notation system from the computational point of view. The goal is to probe if the system can be of some utility for programming and generative grammars. In the first place, *quipus* and di Sangro's work can provide interesting algorithms or techniques for data and data structures. *Quipus* are certainly related with memory palaces, mnemonic tricks used in ancient Greece and Rome that were very popular in the Renaissance[17].

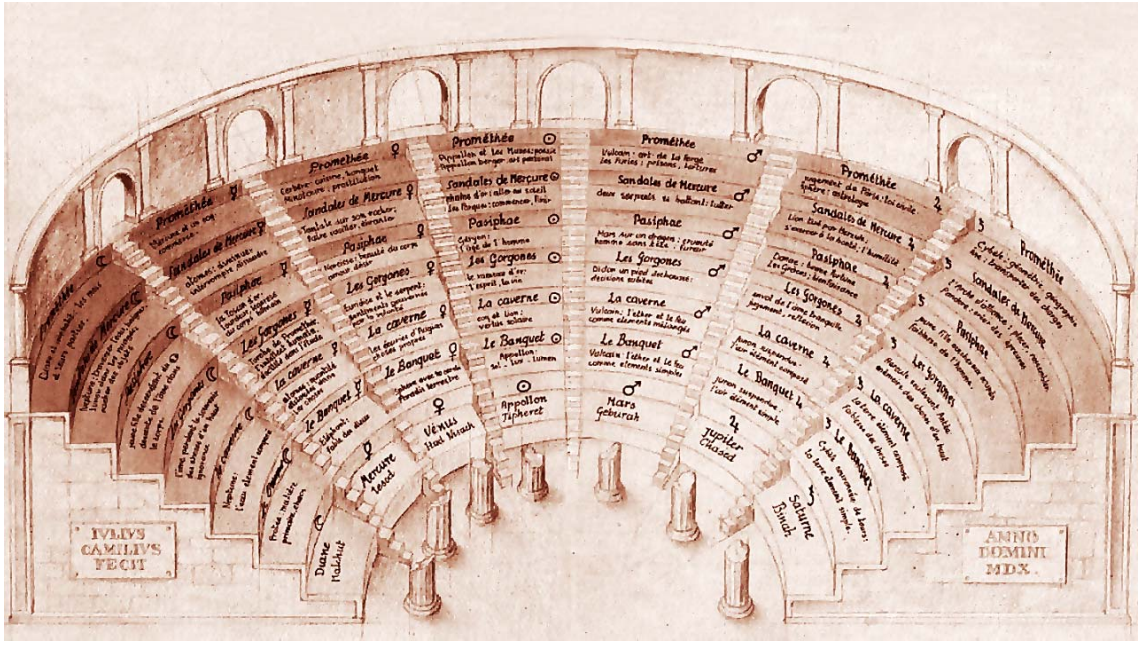


Fig. 9a. Giulio Camillo's memory theater, 1550. https://wsimag.com/culture.

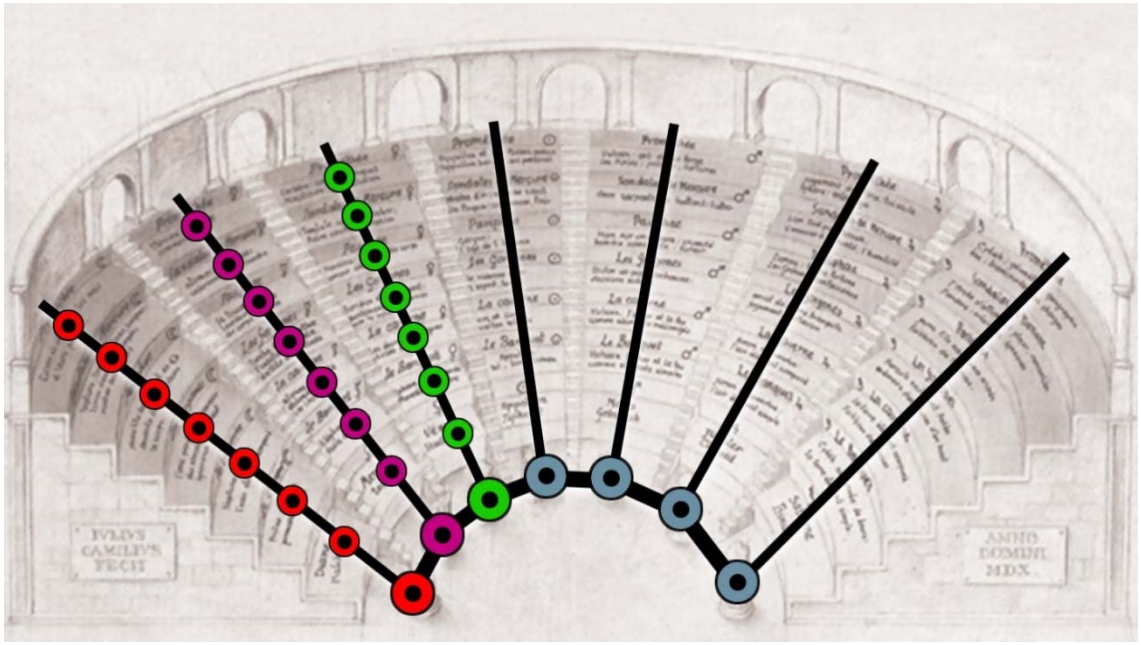


Fig. 9b. Giulio Camillo's memory theater and *quipu.*

The picture of Giulio Camillo's theater of memory shows clearly the relationship between *quipus* and the parts of the structure of theater used to link data: the inner circle is where the stairs begins, such as in *quipus* the main string is the point where are attached the strings, and the steps are the knots (fig. 9a and fig. 9b). Nowadays, we do not need memory palaces, since computer

[17] Thanks to humanists like Matteo Ricci. Memory palaces are mental architectures in which imaginary rooms we stores data and information. The relationship with the different rooms helps to strength links in our memory. Palaces and theaters of memory are similar to ancient Hindu systems like Melakarta, used to visualize notes and musical scales.

memory is a memory palace, whose locations we access using variables and pointers. The CPU does this work for us.

Nevertheless, di Sangros's system can teach something about data structures. For example, each *quipus*' string is clearly a sort of linked list, a data structure well known in computer science[18]. There is a similar logic shared by the knots of a *quipu*'s string and the nodes and pointers of a linked list.

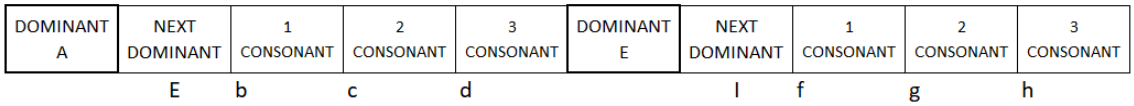


Fig. 10. The dominant-consonant positional system of letters using *quipus*, implementing RdS hypothesis. The links can be changed using context grammars, for instance, to select to jump to the following dominant or to one of the consonants.

We can validate the logic behind *quipus* by comparison with notation systems and code not only from Greece and Rome, but also from medieval Hindu mathematicians and scholars, like the musical charts of *Melakarta*.

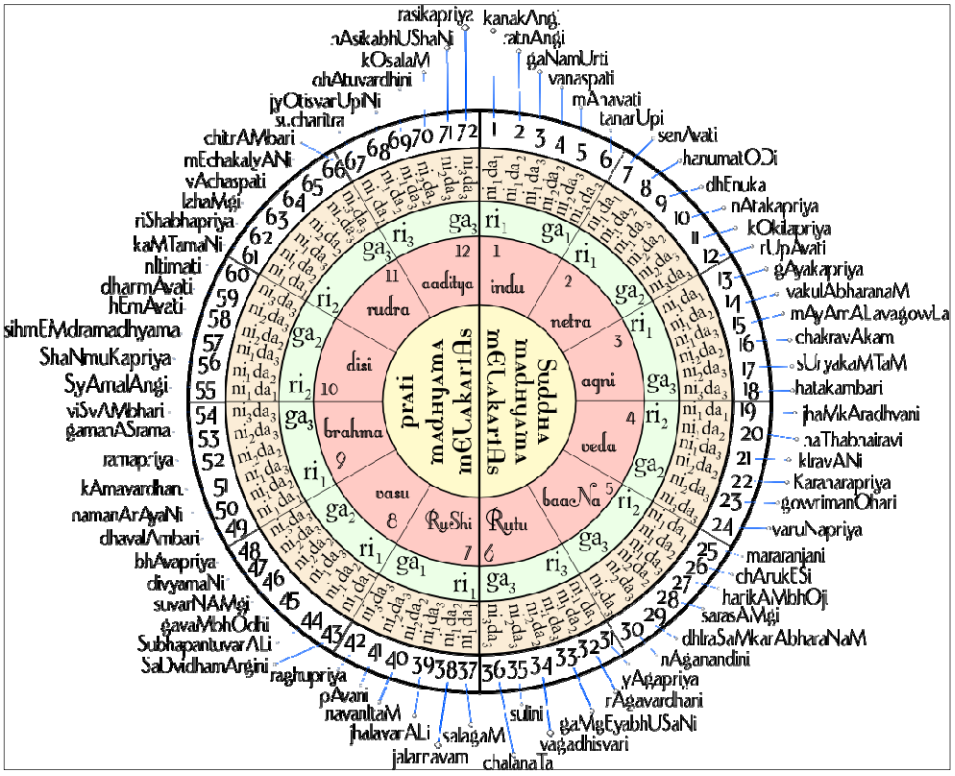


Fig. 11. *Melakarta* diagram.

Quipus and generative grammars

However, in the scope of programming and generative art, the work of di Sangro is a lot more interesting. For instance, his system can help to improve the representation of the structure of classes, methods and properties in object -oriented programming languages, such as ULM. Very often code is too difficult to understand, and this is especially true in the case of generative software.

[18] A linked List is a sequence of links, which contains items. Each link contains a connection to another link. Linked list is the second most-used data structure after array.

Besides, di Sangro's notation could help to generate coherent rule systems, to make substitution processes simpler and, at the same time, with more complex results. We all know that Shape Grammars and L-Systems are essentially based on rules. Therefore, the complexity and inventiveness of generative designs depends strongly on rules' logic and the tools to edit, change and interact with the rule system [14]. In addition, we must not overlook the problem of the interface, since complex and original sets of rules could make the programming of recursive systems very difficult. In this paragraph I will enumerate some of *quipus*' computational possibilities and advantages.

Substitution of groups of symbols in parameterized L-Systems

In L-Systems, symbols are usually substituted one by one. But following di Sangro's notation, groups of letters provide an alternative notation to single character substitution. Rules can be applied to groups of symbols, and this makes also possible to reduce the quantity of rules: for instance, we could create a large single rule (that acts as primary word) and select parts of it using context, grammars, predecessors and successors (previous and following symbols). We could select a rule reading a predecessor of distance 1, distance 2 or distance n from the starting symbol of the selected primary word. This distance is obviously a parameter. Complex forms can be subdivided in smaller parts using different symbols, and the selecting the part that correspond to a specific distance in the primary word. This improves the control of self-similarity of forms. The technique is pretty simple. Suppose to write a complex rule for symbol a using 3 symbols, a, b, c (it does not matter what the rule actually means):

a = ***bbbP<bbYccccXddd***

This rule can be divided into 3 parts, like a primary word of di Sangro:

Part 1: ***bbbP<bb*** Part 2: ***Ycccc*** Part 3: ***Xddd***

So if we want to use one of these parts of the rule, or all of it, we can analyze the string to be processed, or axiom "bacada" and get the predecessors of the 3 instances of symbol "a", that is "b" for the first "a", "c", for the second "a" y "d" for the third "a". The predecessor identifies which part of the rule to use:

Axiom	instance 1, pred. b	instance 2, pred. c	instance 3, pred. d
bacada	a(b)= ***bbbP<bb***	a(c)= ***Ycccc***	a(d)= ***Xddd***

So the result will be:

b bbbP<bb c Ycccc d Xddd

This approach has more benefits: increasing rules complexity also improves the recursive process' control and the creative possibilities of the generative grammar[19].

Quipus and generative grammars interfaces

As already said, the main problem of any recursive process is that is tricky to control and monitor along its development. Moreover, a weak interactivity causes predictability and repetition (albeit you use pseudo random numbers) and creativity is jeopardized. For this reason, shape grammars and L-Systems are not really user friendly. A new challenge is to design and edit a set of complex

[19] These improvements include new algorithms and symbolic notations for special L-Systems techniques. For more details on this subject see my contribution to the Generative Art Conference in 2016 [14].

rules that change over time and must be modified during the process.
That's why the goal of this research is to develop manipulation and editing of shape grammars and L-Systems in more flexible ways. Considering the problem of visual representation of rules and functions in L-Systems or shape grammars applications, *quipus* are interesting because its textile metaphor can be translated in GUI designs, to make the manipulation of symbols and rules more intuitive.

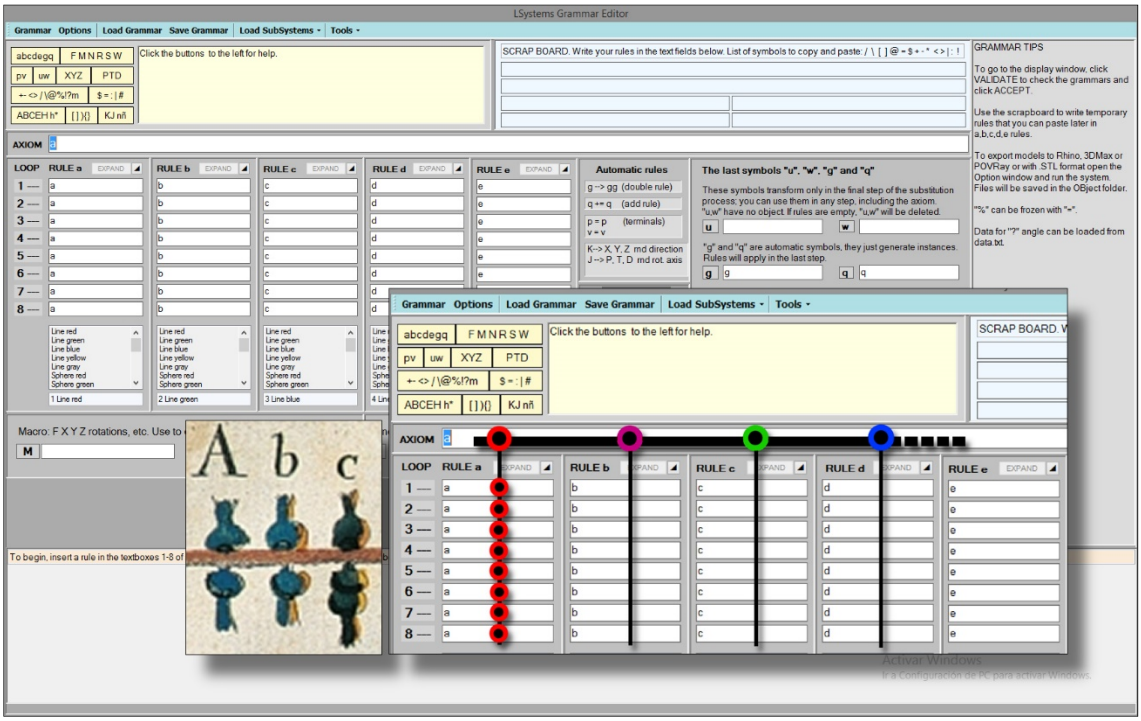


Fig. 12. Detail of di Sangro's illustration, and interface of my L-System generator (free download from http://www.digitalpoiesis.org)

As you can see in fig. 12, from symbols "a,b,c" depart sequences of rules, whose distance from the symbol (the dominant, in RdS solution) identify not only the rule, but the level of the recursive process in which it will be applied.
It is also possible to repeat a rule n times (look at the column "LOOP" to the left of fig. 12) and this is like *quipus*' knots, whose complications have a numerical meaning: 1 complication = 1 step/loop, 2 complications = 2 steps/loops, and so on (fig. 2a).

Conclusions

In this paper I made a synthesis of parts of the di Sangro's eighteenth century book *Lettera apologetica*, about the characteristics of *quipus* and its alfanumerical codification as a writing system. Di Sangro's and contemporary studies about *quipus* are still hypothesis to be confirmed by further research. In fact, the comparison between *quipus*, *mnemotechnics* and contemporary computational data structures shows that the ideas of di Sangro deserve the effort.
In this paper I tried to elucidate the analysis of di Sangro, since the book is quite complicated to read; plus, considering that no translations in English or Spanish are available, I hope that my resume could help scholars, programmers and artists comprehend how *quipus* could work or could be used for art and programming. To support this, I worked on to cases: rule design in L-Systems and interface design for Shape Grammars and L-Systems applications.
Finally, it is important to mention that other old Peruvian artifacts could be of computational interest. For instance, knots textiles [10] and *tokapus* [18], complex textile patterns that were probably a sort of communication code.

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