The ties that bind: Computational, cross-cultural analyses of knots reveal their cultural evolutionary history and significance

Roope O. Kaaronen[1*], Allison K. Henrich[2], Mikael A. Manninen[1], Matthew J. Walsh[3], Isobel Wisher[4], Jussi T. Eronen[1,5,$], Felix Riede[4,$]

** Corresponding author. roope.kaaronen@helsinki.fi*
$ Shared senior authors
1 PAES Research Unit, Faculty of Biological and Environmental Sciences, University of Helsinki, Helsinki, Finland
2 College of Science and Engineering, Seattle University, Seattle, Washington, USA
3 Modern History and World Cultures Section, The National Museum of Denmark, Copenhagen, Denmark
4 Department of Archaeology and Heritage Studies, Aarhus University, Aarhus, Denmark
5 BIOS Research Unit, Helsinki, Finland

Keywords: knot theory, cultural evolution, technological evolution, cognition, anthropology, archaeology, cognitive technology

1. Abstract

Integral to the fabric of human technology, knots have shaped survival strategies throughout history. As the ties that bind, their evolution and diversity have afforded human cultural change and expression. This study examines knotting traditions over time and space. We analyse a sample of 332 knots from 83 ethnographically or archaeologically documented societies over ten millennia. Utilising a novel approach that combines knot theory with computational string matching, we show that knotted structures can be precisely represented and compared across cultures. This methodology reveals a staple set of knots that occur cross-culturally, and our analysis offers insights into their cultural transmission and the reasons behind their ubiquity. We discuss knots in the context of cultural evolution, illustrating how the ethnographic and archaeological records suggest considerable know-how in knot-tying across societies spanning from the deep past to contemporary times. The study also highlights the potential of this methodology to extend beyond knots, proposing its applicability to a broader range of string technologies.

2. Introduction

The use of materials like plant fibres, leather, rawhide, or sinew to twine, bind, or secure objects is an ancient human technology [1,2]. Whether employing a simple strip or utilizing twined or corded materials – collectively known as 'string' – this practice has long been fundamental to human innovation. The full functional efficacy of string as a technology is realized, however, once one or several pieces of material are combined, and it is used to knot together different things. As the ties that bind, knots have played a considerable role in the combinatorial explosion of human composite technologies. In tying a knot, the cognitive capacity to imagine a specific string configuration – its topology – is enacted manually in a goal-directed transformation that results in specific functional affordances. While knots have a fundamental technological purpose, they can also be conceived of as 'tools of the mind' [3–5]. As such, they are part and parcel of human cultural and technological evolution. Knot-making was requisite knowledge which must have been passed on through social learning as early as the Lower and Middle Palaeolithic. For example, knotting is implicated in the lashing of early dwellings and hafting of tools [6] and in the earliest strung beads and ornaments ranging back to 120–160 thousand years ago [7]. Human mastery of knots has catalysed the cultural evolution of a swathe of other technologies, ranging from textiles and garments to hafted and composite tools and weapons, nets, snares, transport technologies, and ornaments. Virtually all traditional human technology involved knots [8]. The human intrigue with knots has come a long way: today, thousands of knots are known [9,10], with knot theory extending its reach into domains such as DNA and protein modelling [11,12] as well as quantum computation [13].

Although knot-tying is still considered common knowledge, the role and knowledge of knots in everyday life has diminished markedly in most aspects of the industrialised world. Beyond scouts, climbers, sailors, knot-enthusiasts, and other practitioners of traditional knowledge (net-makers, weavers), the knot repertoire of most people today is meagre. Today, most knots are made for us, not by us – often by machines – or they have been replaced by other solutions. In both contemporary and past non-industrial societies however, knots play a much more pervasive role in day-to-day activities. Knot-making is a prerequisite of many subsistence behaviours, requiring extensive knowledge of diverse knot types and their uses; to tie a seaworthy kayak securely with sinew is no simple task [14]. In addition, knot-making can be intensive and time consuming: activities dependent on knot production, from net-making and mending to crafting intricate textiles, may require hundreds of hours of work, coordination, collaboration, and elaborate, staged operational sequences [15]. Throughout most of human history, knots and knot-tying have been an intrinsic part of daily life and a vital part of the human cultural niche.

Beyond their most common practical uses (Box 1; Fig. 1), knots have found their ways into various aspects of human experience. Across societies, they are recurrent themes in literature and symbolism, often representing connections such as bonds of love, intimate relationships or trust [16]. But their symbolic utility goes well beyond this. Famously, the Inka used a system of knotted strings called 'quipu' (meaning 'knot' in Quechua) as a language for administrative record keeping and for other important documentation [17]. In Marquesas, knots have been used as genealogical mnemonics, helping to memorize a literal social ‘network’ [18]. Knots are also common ornaments, from Polynesian sennit [18] to Celtic [19], Norse [20], Japanese, and Chinese [16] ornamental knots. Ornamental carvings of knots can be found as early as ca. 2500 BCE in Mohenjo-Daro [21], and are ubiquitous in ancient Greek and Egyptian art [22]. Knots are a common topic in folklore and mythology, the most famous Western example being the legend of the Gordian knot [22]. Knots were also key to ancient medicine [e.g., 23], since they are required in surgery and in the making of slings and tourniquets. Knots are utilized even in martial arts such as the Japanese Hojōjutsu [24].

Box 1. Basic knot terminology.

Stopper: an end knot that creates a bulkier mass at the end of the cord, preventing the cord from unraveling, or preventing an object from accidentally passing through a string.

Bind: a knot used to tie objects together.

Bend: a knot used to tie two ropes or strings together to create one, extended, cord.

Hitch: a knot used to tie an object around a pole.

Mesh: a knot used in the mesh of a net.

Braid: a braided knot-like pattern.

Lashing knot: a knot used to bind two or more poles together.

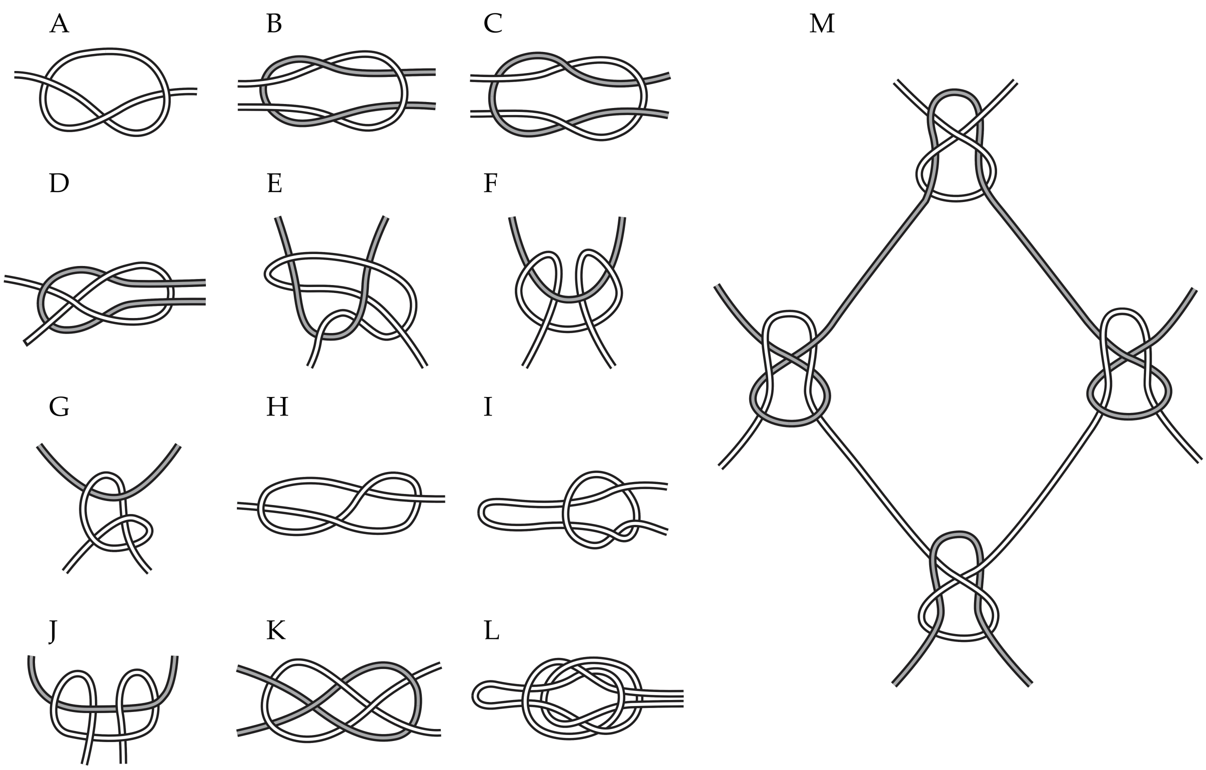
Coil: a knot formed by wrapping a rope around itself to create a coiled shape, commonly used for storing a rope.

Heaving line: a heavy knot tied to the end of a rope, making the rope easier to throw.

Knots thus have deep cultural significance well beyond their functional purposes. The emergence and transmission of knot-making behaviours has been discussed by ethnographers [25–30], archaeologists [31–33], and cultural evolution scientists [34–38], with each emphasising the importance of knots in shaping technological and cultural development. Yet, to date, it is not sufficiently known whether there are regional or chronological patterns in human knot-making, or whether certain types of knots share a deep evolutionary history. As potential patterns have not been mapped, it has not been possible to robustly reconstruct the cultural evolutionary history of knot-tying.

Utilizing the ethnographic and archaeological archives of Human Relations Area Files (HRAF), we conduct a first-ever global, cross-cultural analysis of knot-tying traditions. To achieve this, we develop a methodology that combines knot theory and computational string matching [39]. Transforming knotted strings into numeric strings affords an unambiguous mathematical representation of knots. In turn, this facilitates rigorous downstream computational analysis and comparison. Our ethnographic and archaeological corpus of 332 knots from 83 societies around the world spans approximately 10,000 years, allowing us to distil the repertoire of most ancient knots whose history, we assert, likely extends much deeper into prehistory than the ten millennia represented in our dataset. Our analysis stresses the role of knot-making in human cultural and technological evolution, pointing to evidence of notable know-how in knot-making across time and cultures. Our results open several promising research avenues for future research in the realms of prehistoric and early modern knotting and textile traditions around the world. Notably, we highlight how the proposed methodology could be applied to study any object made of string, potentially allowing cross-cultural analyses of string technologies across large datasets.

Figure 1. *A collage of some common knots.* ***A.*** *Overhand knot.* ***B.*** *Reef knot (square knot).* ***C.*** *Granny knot.* ***D.*** *Sheet bend (weaver's knot).* ***E.*** *Sheet bend, alternative form (by pulling the bottom left string, the rightmost crossing moves to the centre, resulting in a knot isomorphic to 1D).* ***F.*** *Cow hitch (lark's head), netted form (hitched to another string).* ***G.*** *Palaphitic net knot* [40] *(a half-hitch tied around another string).* ***H.*** *Figure-eight knot.* ***I.*** *Slip knot (slipped overhand knot).* ***J.*** *Clove hitch.* ***K.*** *Carrick bend.* ***L.*** *Bottle sling (jug sling).* ***M.*** *A series of sheet bend knots with alternating orientations on every other row, modelled after a Khoisan sinew net bag* [41].



3. Materials and Methods

Different knot types are often difficult to distinguish from one another simply by eye. Knots may have a similar overall appearance (e.g., they may produce an identical shadow or visible topology) yet differ in minute details, as for instance the square knot and the granny knot in Fig. 1B–C. The same knot may be depicted from various orientations, mirrored, be presented in a tight or loose form, or made with variable materials, all resulting in a drastically different appearance, while having the same underlying topological structure. Yet, knots can be reliably described using formal mathematical theory. Such theory has previously been applied in the study of knot-making traditions [35] but without allowing the quantification of knot (dis)similarity in a way that facilitates quantitative cross-cultural comparison and string matching. Based on our previous work on string figures [39], we present a generalizable method that uses Gauss code [42] to transform string technologies into numerical strings. We use this approach here to reliably identify and match knots according to their similarity.

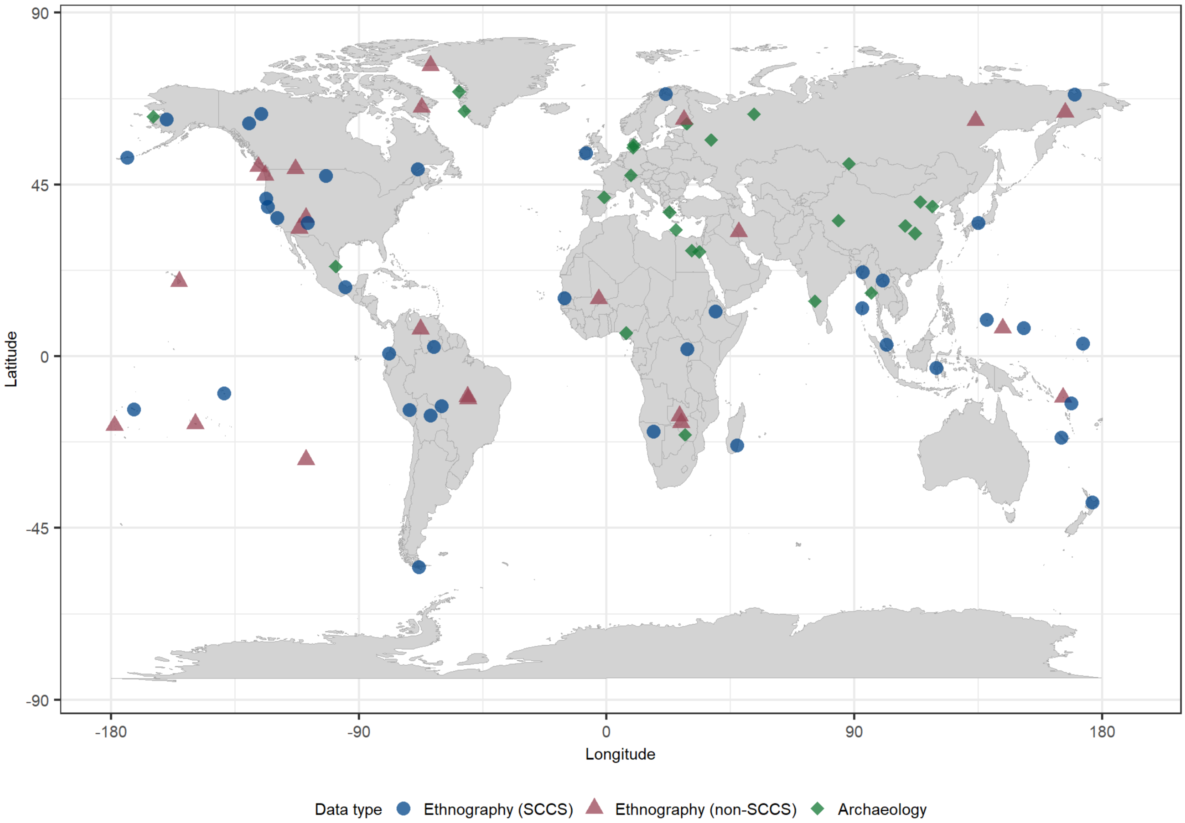
Data collection

We queried HRAF's ethnographic and archaeological online databases, eHRAF World Cultures and eHRAF Archaeology, for all depictions of knots. Our search consisted of both a keyword- and subject-based search. Paragraphs of eHRAF documents have been coded with subject identifiers based on the Outline of Cultural Materials (OCM) classification system. OCM subject #284 covers 'Knots and Lashings'. We searched through all 1779 paragraphs with this subject identifier, collecting all pertinent images of knots whose topological structure could be deciphered. Since not all knots have been annotated with this OCM tag, we complemented this search with a keyword-based search on eHRAF (both World Cultures and Archaeology), using keywords *knot**, *net**, or *fig** to harvest any additional figures of knots and netted items. Finally, to account for regions less intensely covered by HRAF (mostly, Europe and Asia), we also conducted a literature search for anthropological and archaeological literature on knot traditions.

In total, our sample consists of 332 knots from 83 societies or archaeological traditions. 91 knots are from archaeological finds and 241 from ethnographical descriptions. 199 of all knots are from HRAF. We did not include the knots from the Ashley Book of Knots (ABoK) [9] in our analysis. Knots in ABoK have already been formally analyzed elsewhere [35] and ABoK contains little to no information on the cultural origins of its knot collection, rendering it of limited use for cross-cultural analyses. In accord with knot-tying traditions, we have matched the knots in our sample with their ABoK counterpart where possible, and we refer to ABoK-defined knots with their respective number (#).

We only collected knots that are accompanied with visual evidence (illustrations, diagrams, photographs, etc.). The reason for this is threefold. First, only diagrams of knots can be Gauss coded, so our methodology is only applicable to images of knots. Second, we have found verbal descriptions of knots unreliable, as many ethnographers have not been especially familiar with knotting or knot names, and lookalike knots are often mislabelled; knots are also often described with catch-all phrases (e.g., 'overhand knot' may sometimes mistakenly refer to any kind of stopper knot). Third, most of our data are described in the early 20th century, and since then knot terminology has changed considerably.

Figure 2. *A map illustrating the origins of the knots in the dataset. Knots are categorized based on whether they are documented in ethnographic or archaeological records. Ethnographic knots from societies in the Standard Cross-Cultural Sample are included as a separate category.*

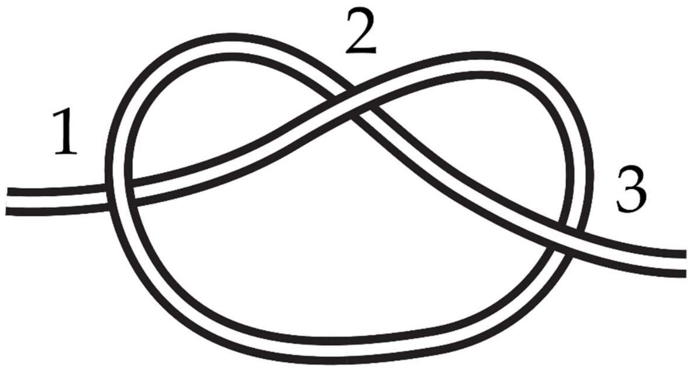


Gauss coding

We use a variation of Gauss code, a standard method in knot theory [42–44], to encode the structure of the knots in our sample. Gauss code is typically used to study mathematical knots. It is important to note that what we colloquially refer to as a 'knot' is almost never a mathematical knot. A mathematical knot consists of a closed loop without loose ends embedded in three-dimensional space (a mathematical knot cannot be untied). In contrast, the practical knots we use in everyday life are typically tied from one or two separate strings, leaving two or more loose ends that can be untied (mathematicians call these configurations 'tangles' [45]). We developed a specific variation of Gauss code that is suitable for the analysis of practical knots and other string artifacts. To avoid confusion, when referring to practical knots we use the word 'knot' and refer to mathematical knots with the term 'mathematical knot'.

The Gauss code used here is best explained with an example. When a knot is made from a single strand of string, simply pick one end of the knotted string (the *basepoint*) and move towards the other end. This determines the *orientation*, the direction to follow while recording each intersection where the string crosses itself. These *crossings* are labelled with the natural number sequence 1, 2, 3, …, n where n is the number of unique crossings in the knot. Every unique crossing is labelled once when it is first encountered. When a crossing is encountered for the second time, it is skipped, and numbering is continued from the next unique crossing. When all crossings are labelled once, the knot is given a Gauss code by 'walking' through the knot (using the same basepoint and orientation) and recording the value of each crossing encountered. These values are sequentially appended into a string of integers. When the string followed lies at the top layer of the crossing (overpass), it is recorded as a positive integer, and when it is on the bottom layer (underpass), it is recorded as negative. Accordingly, the Gauss code for the overhand knot (Fig. 3), from left to right, is -1 2 -3 1 -2 3.

Figure 3. *An overhand knot, the simplest of all knots, Gauss coded starting from the left. If the loose ends were tied together, the overhand knot would be topologically equivalent to the trefoil knot (the simplest non-trivial mathematical knot).*



In our system, to enable cross-sample comparisons, we employ a strict rule: the Gauss code must always start with ±1, proceeding so that each subsequent unique number in the string follows the natural number sequence. Each potential configuration of Gauss code must also be accounted for. Starting from the right end, we would relabel the previous Gauss code 1 -2 3 -1 2 -3. Since the knot could also be viewed from behind, we must account for such 'negative' Gauss codes. These can simply be acquired by multiplying all numbers in a Gauss code by -1. Previously, we have developed the algorithm *GaussCodeR* (described in detail in [39]), which automates the generation of alternative Gauss codes (provided that one Gauss code is provided manually). We use an application of the *GaussCodeR* algorithm for the present analysis. Thus, for single-stranded knots, only one Gauss code is required to generate all possible Gauss codes. We may then represent this knot with a profile of four strings of Gauss code (Table 1). Having this full set of Gauss codes ensures that no matter how an overhand knot is presented, it can be matched with a topologically equivalent knot in any given dataset of knots.

Table 1. *A profile of Gauss codes for the overhand knot.*

Orientation/basepoint	Gauss code
Left to right	-1 2 -3 1 -2 3
Right to left	1 -2 3 -1 2 -3
Left to right (negative; viewed from behind)	1 -2 3 -1 2 -3
Right to left (negative; viewed from behind)	-1 2 -3 1 -2 3

We match strings using q-grams, a method we have previously used for the matching of string figures [39]. With q-grams, each Gauss code in the table above is cut into sequences of length q. We use q = 2 for computational reasons: since a string in a knot may have as few as two crossings (see, e.g., the dark string in Fig. 1G), we use 2-grams for our analysis. To return to the previous example, the overhand knot Gauss code 1 -2 3 -1 2 -3 can be broken into the following 2-grams: '1 -2', '-2 3', '3 -1', '-1 2', and '2 -3'. Doing this for each row in Table 1 allows constructing a q-gram profile [46] for the knot, producing a matrix accounting the occurrence of each 2-gram in the knot's set of Gauss codes. These q-gram profiles can then be compared using distance metrics. We use cosine distance [46], which produces a convenient (dis)similarity metric in the range from 0 to 1 [39]. Any image of an overhand knot – no matter whether mirror or reverse – would have a cosine distance of 0 (entirely similar) when compared to the knot in Fig. 3. Similar but not identical pairs of knots would have a low cosine distance; knots that share no substructures have a cosine distance of 1. This allows the unambiguous matching of knots in a large dataset.

The procedure above can in principle be generalized to compare any two items made with n strands of string. For present purposes, we limit our analysis to one or two-stranded knots (2-tangles), since three-stranded knots are rare and would require additional methodological consideration (see Discussion). The above method is slightly complicated when dealing with two-stranded knots. For an example of a two-stranded knot, consider the reef knot (also known as the square knot): The reef knot (Fig. 4) is made of two strings (here denoted S*n*), both of which have two potential basepoints (BP*n*). Unlike the overhand knot (which only has two basepoints), we could start labelling the reef knot from four distinct basepoints. This produces some extra combinatorial problems that must be solved, since using our method of Gauss code, the annotation of the second string is always dependent on the first one. Starting from string 1 basepoint 1 (S1BP1, Fig. 4 top-left) we get the Gauss code '-1 2 -3 -4 5 -6'. We call this the *base* string. To complement this, we must also Gauss code the *auxiliary* string (S2). This can be done in two orientations, starting from either S2BP1 or S2BP2. These *auxiliary* Gauss codes are '4 -5 6 1 -2 3' and '3 -2 1 6 -5 4'. Note that in this knot, the second auxiliary code is simply the first one in reverse, but this is not always the case. In a two-stranded knot, the base string must always start with ±1, but the auxiliary strings may follow any necessary order of numbers. The auxiliary string may also introduce new crossings, and in those cases the natural number sequence is followed as usual.

Figure 4. *A reef knot Gauss coded in all possible configurations of basepoints and orientations. Starting from S1BP1, the knot is thus given three strings of Gauss code: the base code '-1 2 -3 -4 5 -6', and the two auxiliary codes '4 -5 6 1 -2 3', '3 -2 1 6 -5 4'. When the same logic is repeated for all four basepoints, we gain 12 strings of Gauss code (Table 2).*

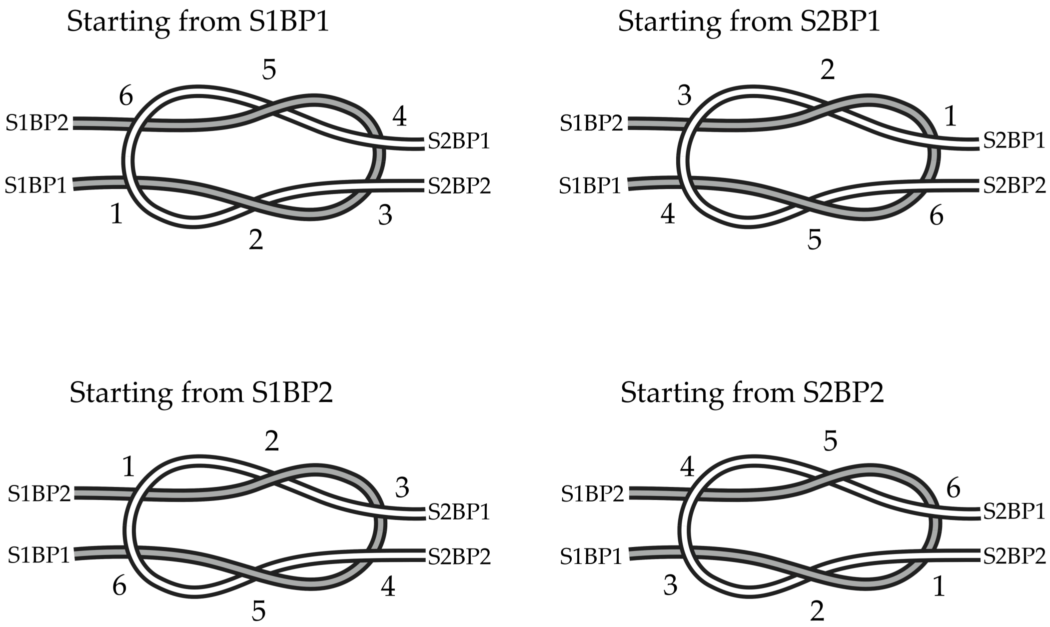


Table 2 documents all the Gauss codes we obtain from Fig. 4. In practice, the order of recording these 12 Gauss codes does not matter as long as they are all accounted for. Again, multiplying all 12 Gauss codes by -1 produces the negative image, resulting in a total of 24 Gauss codes for any two-stranded knot. The validity of Gauss code is readily verified. Each single strand knot will be represented with Gauss code that must have a matching positive integer for each negative one. In a two-strand knot, appending the base string with one of the auxiliary strings effectively produces a Gauss code for a mathematical knot (sometimes a virtual knot [47]), which also must have a matching positive integer for each negative one.

Table 2. *Gauss codes for the reef knot, all possible configurations.*

Base at S1BP1	-1 2 -3 -4 5 -6	Base at S2BP1	1 -2 3 4 -5 6
Auxiliary #1 for S1BP1	4 -5 6 1 -2 3	Auxiliary #1 for S2BP1	-4 5 -6 -1 2 -3
Auxiliary #2 for S1BP1	3 -2 1 6 -5 4	Auxiliary #2 for S2BP1	-3 2 -1 -6 5 -4
Base at S1BP2	-1 2 -3 -4 5 -6	Base at S2BP2	1 -2 3 4 -5 6
Auxiliary #1 for S1BP2	4 -5 6 1 -2 3	Auxiliary #1 for S2BP2	-4 5 -6 -1 2 -3
Auxiliary #2 for S1BP2	3 -2 1 6 -5 4	Auxiliary #2 for S2BP2	-3 2 -1 -6 5 -4

In theory, any knot can be annotated in this way. In practice, some complex knots may be inconvenient to code, and some caveats arise. Gauss code assumes a knot diagram: a 2-dimensional projection of a knot onto a plane. But some knots are three-dimensionally complex, such as the 'monkey's fist' (a well-known heaving line knot shaped like a ball, which can be traced to Han dynasty China [16]). While such knots can be unentangled and laid out on a two-dimensional surface, the precise way in which they are unravelled might result in arbitrary decisions that could affect the coding process. Depending on how a knot is presented, it may be sometimes Gauss coded in more than one way (see Fig. 1D–E for two common ways of representing the sheet bend). To ensure that such knots are reliably matched, we recommend Gauss coding these knots in all sensible layouts. Since the q-gram method compares knots on the substructural level, it typically performs well in identifying different layouts of the same knot, recognising their similarity. These caveats in mind, if a knot is relatively flat, even very complex configurations can be Gauss coded reliably, and our dataset includes knots up to 64 crossings long. Note that knots may also be embedded in a net or other larger structure of cordage. For instance, a mesh knot (Fig. 1M) is embedded in a net, where many knots form a cohesive structure. In such cases, before conducting the steps described above, the knot (the minimal repeating pattern) must be extracted – digitally cut out – from the surrounding structure prior to analysis.

Clustering

Once each knot in the dataset is Gauss coded, the q-gram profiles of knots are compared in a cosine distance matrix. This cosine distance matrix is then visualized using hierarchical clustering. Similarly to analyses of string figures [39], we produce a dendrogram using complete linkage clustering. The complete linkage method creates various small and discretised clusters with the assumption that an existing object represents each cluster [see Table 1 in 44]. This is suitable for the present purpose, since we may assume that each cluster is represented by a real knot, and we intend to visualise multiple clusters of structurally variable knots.

Qualitative classification

We are not only interested in the structure of the knots, but also their purpose: the same knot may have variable uses in different cultural contexts. We classified a typology that accounts for both its immediate function – what class of knot it is – and its cultural context – what it was used for. This allows the selection of subsets of knots from our dataset. For example, searching for knots tagged with the qualitative codes 'Fishing' and 'Mesh' would select all mesh knots used in the context of fishing, i.e., fishing nets.

Table 3. *A qualitative coding scheme for knots, accounting for both their cultural context and their functional knot type (see Box 1).*

Code 1: Context	*Code 2: Function*
Livestock: used in the context of animal husbandry (or pets).	**Bind**
Textiles and garments: used in the context of clothes, weaving, knitting, etc.	**Bend**
Fishing: used in the context of fishing.	**Hitch**
Decorative: used in the context of ornamentation, rituals, divination, religion, etc. (without an immediate practical function).	**Mesh**
Hunting: used in hunting (other than fishing).	**Stopper**
Tools: used in the binding or lashing of other everyday tools/weapons.	**Braid**
Communication: used in transmitting messages or accounting (quipu and similar).	**Lashing**
Medical: used as a medical knot.	**Snare**
Construction: used in buildings, dwellings, furniture, boats, etc.	**Coil**
Restraint: Used to tie a person or animal to prevent it from moving.	**Weave**
NA/Other: Data not available.	**NA/Other**

4. Results

We identify 32 cross-culturally recurring knots in the dataset. The data also includes a variety of idiosyncratic or complex knots that appear only in a single society. This illustrates clearly how people around the world have used a set of staple knots to solve a variety of everyday problems. It also highlights how different cultures have experimented with more complex and unusual knots. Fig. 5 presents a dendrogram where the names of the leaves refer to individual knots in our dataset. The outermost clusters of the circular dendrogram contain sets of identical knots. Structurally similar knots (e.g., the reef knot and granny knot) appear in nearby clusters. In Fig. 5, we have named the knots that we were able to identify and, where available, given their respective number (#) in ABoK. However, not all knots in the dataset are documented in ABoK, and many knots are not widely used today and do not have formal or vernacular English names.

The most commonly recurring knots across cultures are the sheet bend (clades #402 and #1497; documented in 29 cultures), overhand knot (#514; 23 cultures), reef knot (#75 and #74; 22 cultures), and cow hitch (clades #5; 19 cultures). We also compare the geographical distribution of identical pairs of knots to non-identical (i.e., all other) knot pairs. A cosine distance of 0 signifies that two knots are identical. If identical knots were shared more commonly between geographically proximate cultures, we should expect these distributions to differ [39]. There is no notable difference in the geographical distribution of identical knot-pairs to non-identical ones (Fig. 6). This suggests that, overall, geographical proximity does not structure knot similarity. This implies that the most common knots are either easily innovated independently or have shared ancestry that reaches back into the very distant past, points which we return to in the Discussion section.

Based on our contextual/functional knot classification we can select and analyse specific kinds of knots. Fig. 7. summarises our dataset based on this classification. Since netting knots are especially common in our dataset, and are also of particular interest in archaeology [49,50], we plot in Fig. 8 the subset of mesh knots that are used in netting, highlighting also the subset of knots used in fishing nets. Although our data portrays a variety of solutions to the net-making problem – nets in our dataset are made with reef knots, palaphitic knots (half-hitches) [40], granny knots (INNU_1), and cow hitches, among others (Fig. 8) – exactly half of the fishing nets in our dataset use a variation of the sheet bend. This is a striking conformity that we discuss further below.

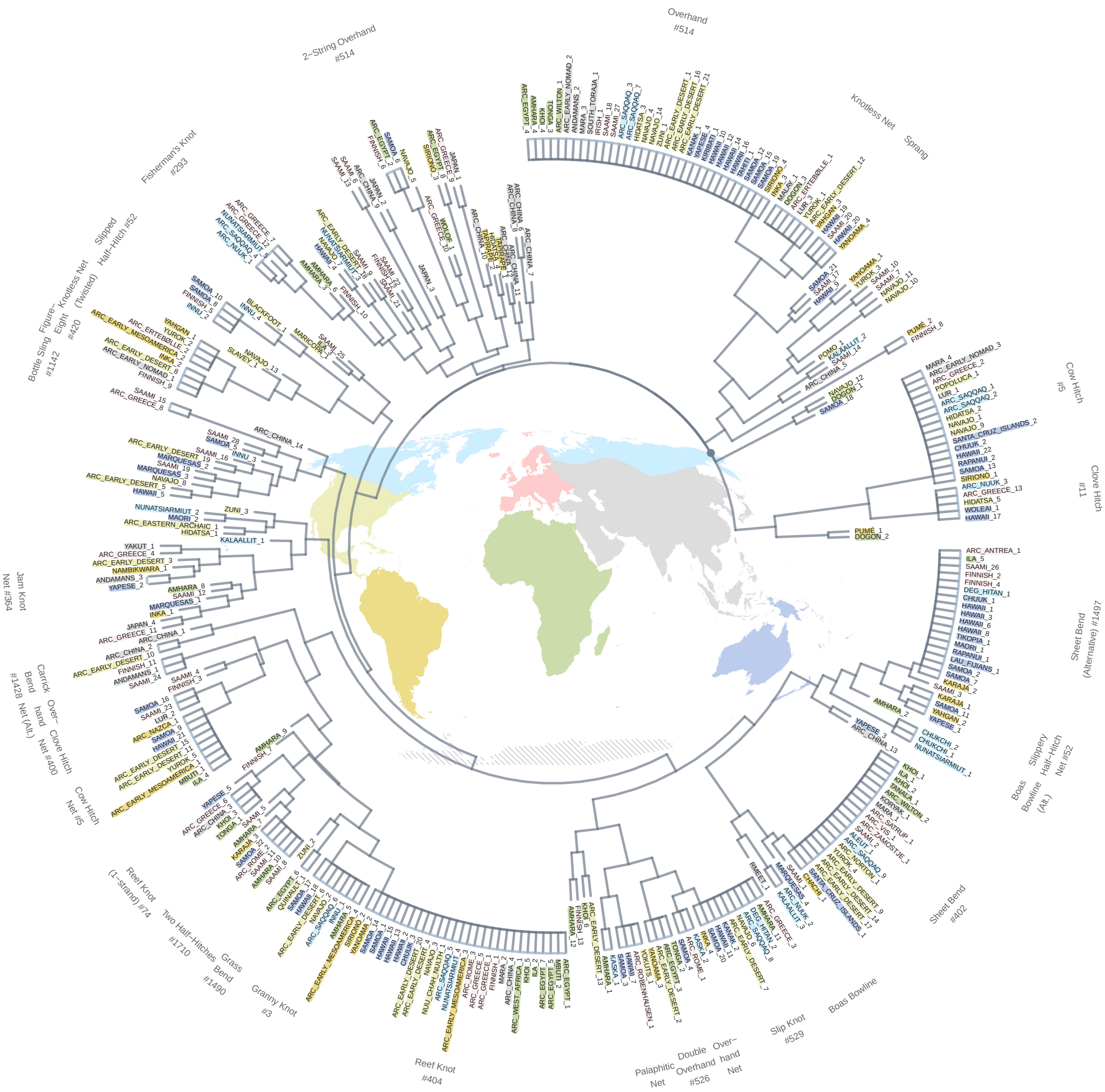


Figure 5. *A phenetic tree (dendrogram) of knots. Clades at the outermost layer contain sets of identical knots and are highlighted with a bar. These clades are named and numbered (based on ABoK) where possible. Clades under the same branch contain structurally similar knots (e.g., the granny and reef knot). Knots from archaeological traditions are labelled with the prefix 'ARC_'. The ggtree* [51] *package is used to create this dendrogram, using complete-linkage clustering. Leaves (individual knots) are coloured by region (see map in the centre of the tree).*

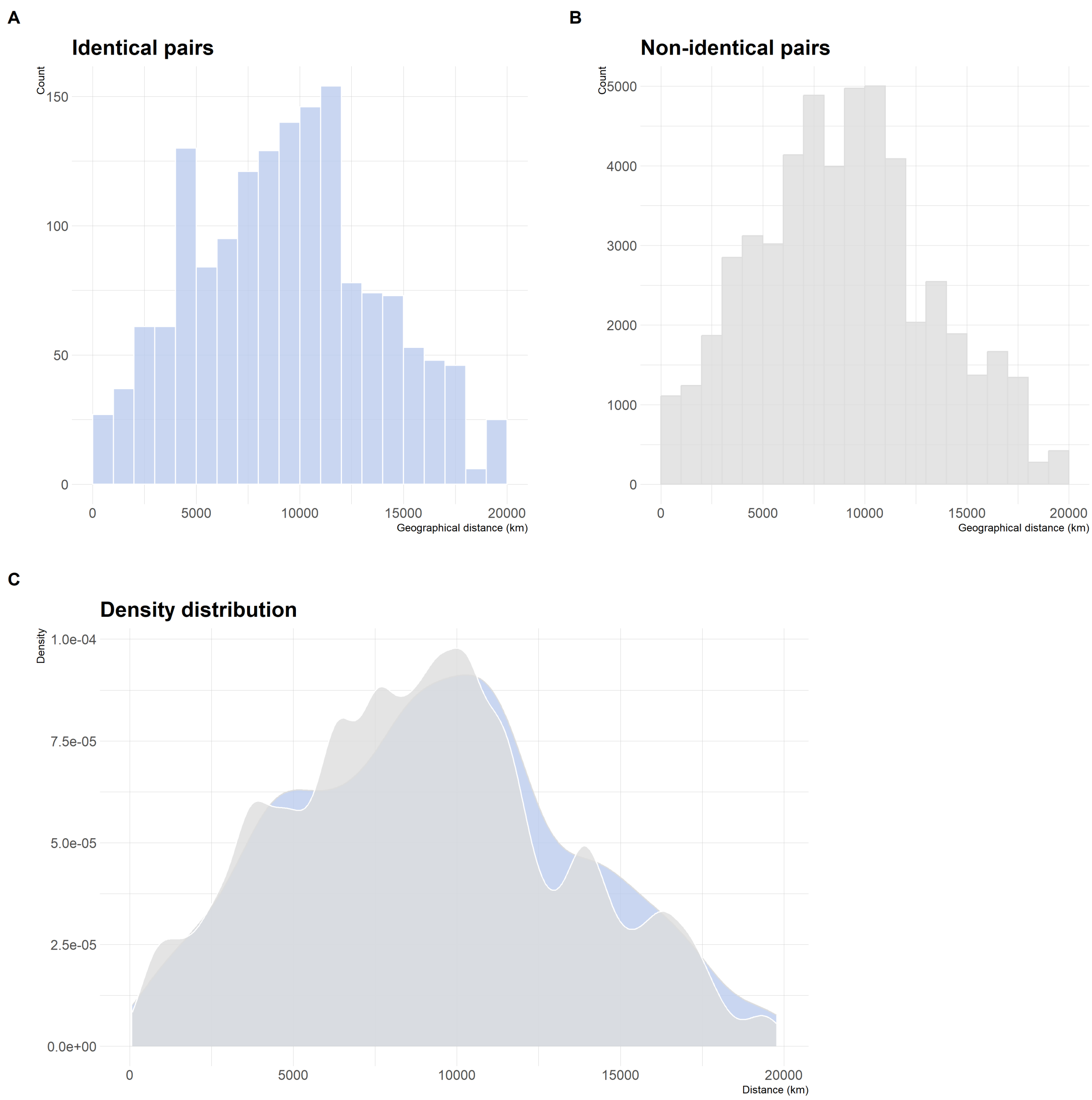


Figure 6. *Histograms illustrate the geographical distribution of structurally identical (plot A) and non-identical (i.e., all other; plot B) pairs of knots. Within-society comparisons are excluded from this analysis. Plot C overlays the smoothed density distributions of histograms A and B, comparing the geographical distribution of identical and non-identical knot pairs. The distributions overlap considerably, implying that geographical proximity does not, overall, have a notable effect on the similarity of knots between societies.*

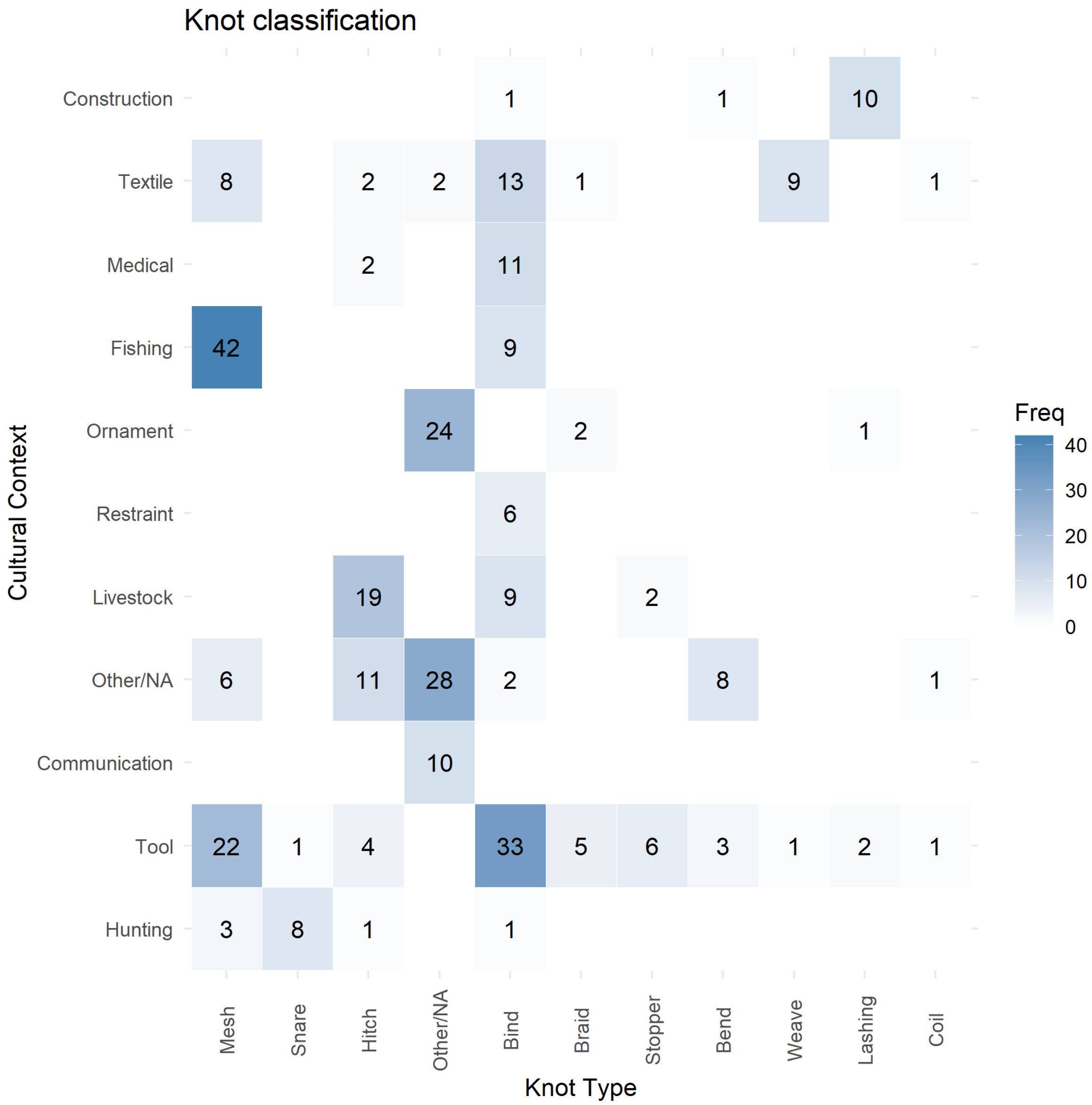
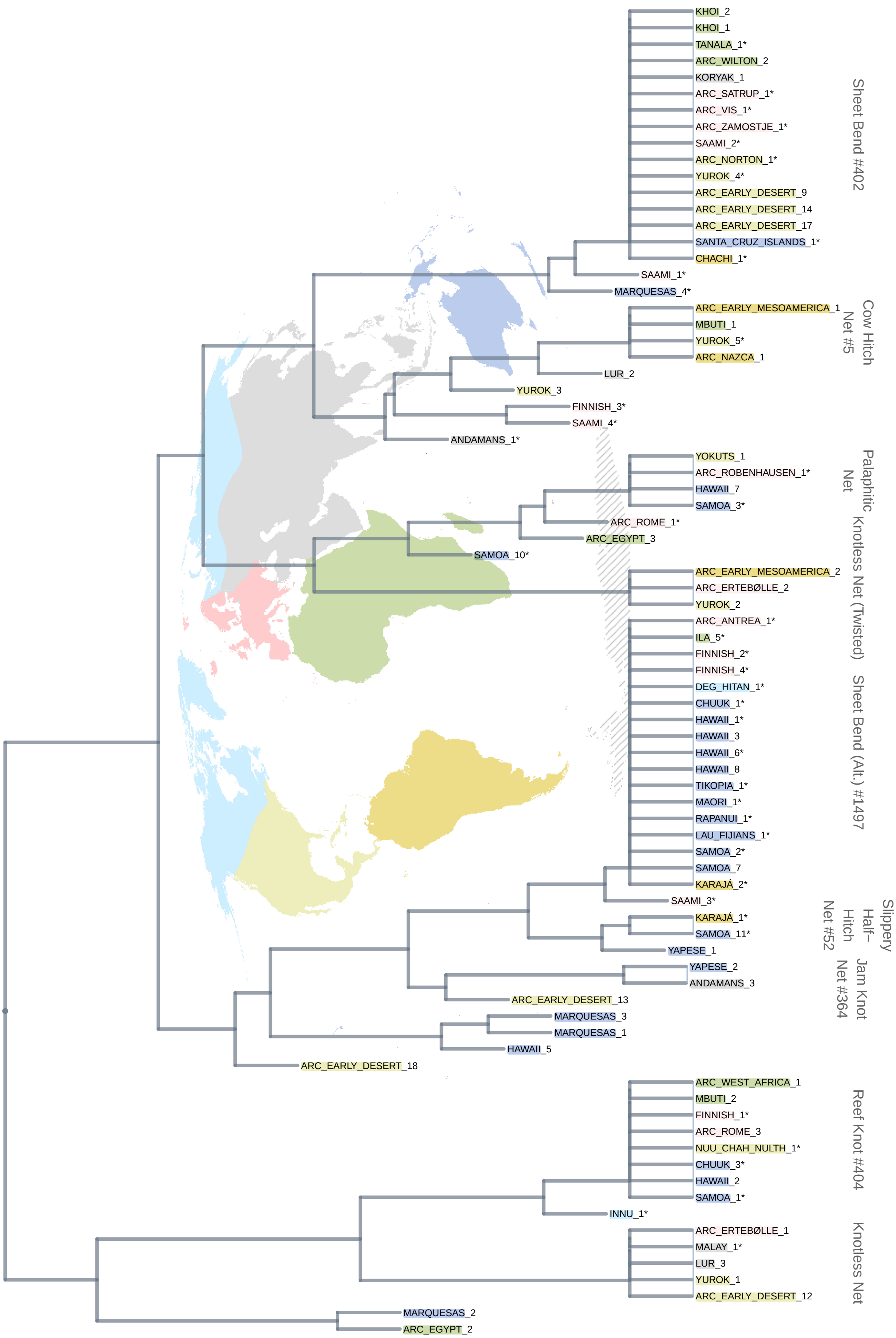


Figure 7. *The occurrence of different types of knots (x-axis) and their cultural context (y-axis). Mesh knots in fishing nets are the most common knot class, followed by binding knots used in everyday tools, ornamental knots, and hitches used for livestock. The missing data is largely due to the presence of archaeological data, where the original function of a knot is often not recoverable.*

Figure 8 (next page). *A dendrogram of mesh knots in our dataset. Fishing nets are marked with an asterisk (*). The sheet bend is the most common mesh knot and an especially common solution for tying fishing nets. The colour scheme is the same as in Fig. 5.*


KHOI_2
KHOI_1
TANALA_1*
ARC_WILTON_2
KORYAK_1
ARC_SATRUP_1*
ARC_VIS_1*
ARC_ZAMOSTJE_1*
SAAMI_2*
ARC_NORTON_1*
YUROK_4*
ARC_EARLY_DESERT_9
ARC_EARLY_DESERT_14
ARC_EARLY_DESERT_17
SANTA_CRUZ_ISLANDS_1*
CHACHI_1*
Sheet Bend #402
SAAMI_1*
MARQUESAS_4*
ARC_EARLY_MESOAMERICA_1
MBUTI_1
YUROK_5*
ARC_NAZCA_1
Cow Hitch Net #5
LUR_2
YUROK_3
FINNISH_3*
SAAMI_4*
ANDAMANS_1*
YOKUTS_1
ARC_ROBENHAUSEN_1*
HAWAII_7
SAMOA_3*
Palaphitic Net
ARC_ROME_1*
ARC_EGYPT_3
SAMOA_10*
ARC_EARLY_MESOAMERICA_2
ARC_ERTEBØLLE_2
YUROK_2
Knotless Net (Twisted)
ARC_ANTREA_1*
ILA_5*
FINNISH_2*
FINNISH_4*
DEG_HITAN_1*
CHUUK_1*
HAWAII_1*
HAWAII_3
HAWAII_6*
HAWAII_8
TIKOPIA_1*
MAORI_1*
RAPANUI_1*
LAU_FIJIANS_1*
SAMOA_2*
SAMOA_7
KARAJÁ_2*
Sheet Bend (Alt.) #1497
SAAMI_3*
KARAJÁ_1*
SAMOA_11*
YAPESE_1
Slippery Half-Hitch Net #52
YAPESE_2
ANDAMANS_3
Jam Knot Net #364
ARC_EARLY_DESERT_13
MARQUESAS_3
MARQUESAS_1
HAWAII_5
ARC_EARLY_DESERT_18
ARC_WEST_AFRICA_1
MBUTI_2
FINNISH_1*
ARC_ROME_3
NUU_CHAH_NULTH_1*
CHUUK_3*
HAWAII_2
SAMOA_1*
Reef Knot #404
INNU_1*
ARC_ERTEBØLLE_1
MALAY_1*
LUR_3
YUROK_1
ARC_EARLY_DESERT_12
Knotless Net
MARQUESAS_2
ARC_EGYPT_2

5. Discussion

Our results show how humans across the world have made very similar knots, and geographical proximity is not an important factor in structuring the similarity of knots between groups. Instead, a staple repertoire of knots appears in cultures over time and space. This core repertoire includes the sheet bend, reef knot, overhand knot and cow hitch, with many other knots also appearing cross-culturally (Fig. 5). Some of the most commonly recurring knots in our sample are the ones one might expect to find. For one, the overhand knot (ABoK #514) is the simplest possible knot to tie. It is made by simply threading a string through its own loop. As such, its ubiquity is unsurprising. The reef knot (ABoK #404 and #74) can be thought of as a composite extension of the overhand knot, producing one overhand knot on top of another [52]. Accordingly, previous research has speculated that knots like these would have been among the first knots humans tied [52]. The prevalence of these knots in both archaeological and ethnographic data, alongside their use in a variety of contexts, supports these suppositions.

However, there are several knots that have a more unexpected ubiquity that cannot be explained by their simplicity. Notably, the sheet bend knot (ABoK #402 and #1497) is more complex than the reef knot – it has one more crossing and is asymmetrical (Fig. 1), yet it is the most commonly recurring knot in our dataset. The sheet bend knot is especially common across Austronesian cultures, where it is used in making fishing nets [25,26,30]. Given the evidence of other similar shared knowledge among Austronesian peoples – including string figures [39,53], sennit [18], and knot divination practices [54] – it is reasonable to assume that this indicates a strong pattern of cultural transmission by social learning in this region.

Sheet bend netting knots have a long history, reflecting their deep and perhaps shared origins across human societies. They are a recurring find in northern European archaeological net finds from bog sites, including the oldest net find, the Antrea net. The structure of the Antrea net knot (carbon dated to 10522 calBP [55]) has caused some confusion – Finnish authors have variably described it being made either with a *köydensolmu* or a *ryssänsolmu*, but have not drawn comparisons to other archaeological finds [56,57]. Our analysis confirms that it is a sheet bend that is illustrated in its alternative form (Fig. 1E). As such, the Antrea net is part of a recurring pattern of sheet bend knots in the northern European archaeological record, with these knots also found in the Final Mesolithic to Early Neolithic bog sites at Zamostje-2 [50], Vis-1 [58], and Satrup [59]. These recurring finds may signal shared knotting traditions among ancient northern European peoples, although further studies on the specific layout of these nets (and the orientation of the knots within) is required to confirm this. Such analyses would be simple to conduct if more complete depictions of the knot structures were available.

Some knots appear to be more geographically exclusive. For example, the so-called 'Boas bowline' [60,61] knot appears in our dataset only in societies residing in the Arctic, from Chukotka to Baffin Island and Greenland. The Boas bowline appears in two clades in Fig. 5 (the reason is the same as illustrated with the similar sheet bend knot in Fig. 1D–E). Similarly, the netted form of the cow hitch knot (#5; Fig. 1F) is common in Mesoamerica and the southern regions of North America. The potential cultural transmission histories of these knots warrants further inquiry. Generally, we may assume that knots are mostly learned through social learning and cumulative cultural evolution. This is because individual trial-and-error with knots has a twofold cost: not only does a poor knot result in malfunctioning equipment and potentially life-threatening accidents, but experimentation would also be particularly costly in time and effort, since intensely knotted technologies such as fishing nets or rugs require hundreds if not thousands of knots to complete.

We have so far mostly highlighted how some well-known knots occur across cultures. Yet it is also worth noting how some knots common in contemporary use are missing from the dataset. For example, even though the bowline knot is today considered one of the most useful knots (it forms a secure loop that does not slip, yet is easy to untie), and despite its similarity to the sheet bend, our dataset includes no bowline knots (other than its Arctic 'Boas bowline' variant, and some other knots with similar features, such as SAAMI_21 and EARLY_ARCHAIC_1). Figure-eight knots (ABoK #420) are rare too, despite this knot being both simple to tie and having a good reputation as a secure stopper knot. The Carrick bend, a secure yet more complex knot for connecting two ropes together, appears only twice in our dataset (ABoK #1428).

It seems that most human societies have settled on a relatively stable repertoire of reliable knots and have not explored thoroughly the topological space of knotting. Arguably, functional efficacy, ease of learning, and ease of tying may have led to such a stable and limited repertoire [62]. Further, knots may be considered technologies under a strong failproof mandate, and the high costs of potential failure may have precluded exploration. In contrast, the state space of string figures [39], a common game or pastime across cultures worldwide, seems to have been explored much more thoroughly and creatively than that of knots. We have previously suggested that string figures may have acted as a creative catalyst for string technologies and the cognitive exploration of string topologies [39], and it may be that the recreational nature of string figures has allowed for more free experimentation when compared to the more practical demands of knots. Some ornamental knotting traditions, like some of the Chinese knots [16] with a range of up to 64 crossings, illustrate more experimental features of knot-tying. The occurrence of such elaborations additionally bolsters the notion that topological experimentation is more likely to be found in recreational or ornamental, and not practical, knot-necessitating activities.

Our data suggests that people across the world have paid meticulous attention to knotting, intentionally preferring more robust knots over unsecure ones. The obvious example is the high prevalence of the sheet bend, which is today a reputable knot for its reliability: it is secure and easy to untie. Another reliable indicator of this is the low presence of the granny knot (ABoK #3). The granny knot is very similar in structure to the reef knot (Fig. 1B–C), both being composite products of two overhand knots. In contemporary knotting traditions, the reef knot is considered an essential knot, whereas the granny knot is notoriously unsecure and prone to slipping. Today, it is regarded a common novice mistake to accidentally tie a granny knot when attempting a reef knot [60]. In short, there is no functional reason to tie a granny knot when one could tie a reef knot. Previous theoretical discussion has suggested that the granny knot is more intuitive to tie than the reef knot, because unlike the reef knot, the granny knot repeats two overhand knots with the same orientation [60]. This has been shown to be the case with experimental work, which suggests that humans have a cognitive or motoric bias to construct the granny knot instead of the reef knot [34]. Against this backdrop, it would be reasonable to predict that in naïve knot-tying populations, the granny knot would appear more often than the reef knot [34]. Yet in our sample the exact opposite is the case. We document the reef knot in 22 cultures, and the granny knot in only 10. Evidently, people around the world have knowingly preferred the secure reef knot over the unsecure granny knot. This may also be indicated in some ethnographical descriptions. For instance, Navajo knot-tying traditions even involve a taboo[1] for using the granny knot for anything other than ceremonial purposes [66]:

> *The granny knot (…) was currently known as the "knot of the dead," and was avoided except in connection with preparation and dressing of the corpse prior to burial. (…) "This knot should never be found on a living person. (…) There are really two knots, one for the living [the reef knot] and one for the dead [the granny knot]."*

Previously, we have suggested that expertise in string technologies may be considered ethnomathematical knowledge [38, see also 66]. String artifacts may be products of a distinctly human 'ethnotopological' way of thinking [39]. Nets are a good example. A net is not a trivial invention and requires considerable expertise and topological reasoning to craft. Some details of nets may suggest deep understandings of topology and net behaviour. For example, as illustrated in Fig. 1M, alternate rows of knots in a net may replicate the same knot in variable orientations – in this case, the sheet bend knots on alternative rows are not only mirror images, but also the 'front' and 'back' version [68] of the same knot. Such designs may be made for several reasons. Alternating knot orientations can ensure that the net maintains a consistent tension and strength throughout its structure, helping it hang properly and preventing the net from buckling [69]. In a fishing net, knot orientations also affect hydrodynamics, altering how a net performs in flowing water [70]. Although such features may also be haphazard, arising simply from the method of weaving (e.g., the turning of the net when knotting alternate rows), we should not a priori dismiss such inventions as mere accidents, since they can also represent purposeful

[1] Note that taboos have been widely associated with practical functions, and they can often be considered precautionary cultural adaptations [63–65].

design-choices that are products of persistent topological experimentation. Some nets in our dataset (e.g., the hunting net coded as MBUTI_1 and MBUTI_2) even use alternating knots (the reef knot and cow hitch) on every other row. These minute details of knot orientations can reveal further information on the methods of how these nets were made [30,68], providing clues as to their evolutionary histories and cultural transmission. Studying these structures in detail, especially across archaeological finds, is a promising avenue for future research, which could also draw on more complete data collected via, for instance, 3D scans of complete nets or video sequences of net production where available.

Not only does knot-tying itself demand a set of peculiar cognitive skills, such as spatial reasoning, memory (recall), fine motor coordination, and analogical thinking [71], it also affords many other quantitative and communicative features. Of these, the Inka quipu already mentioned is perhaps the best documented – an elaborate system of record-keeping and administration that is one of the most well-known examples of ethnomathematics [17,72,73]. However, the case of the quipu is not entirely unique. For example, the Kanak have used similar[2] knots as means to transmit messages [74], and the Zuni have used a base-ten positional knot system for counting and record keeping [75,76]. Knots were also used for administrative records in Zhou Dynasty China [16]. The Amhara have used overhand knot to count grain units for taxation [77].

Consequently, knot-making may have been a catalyst for mathematical and formal thinking throughout human history in various loci [see also 39], and knots may be considered exemplary 'cognitive technologies' [78] – tools that enter into a recursive relationship with cognition and so affect both the hardware and software of human thinking [79,80]. Particularly interesting is the role of knots as combinatory catalysts. Research in technological evolution has highlighted how recombination is essential for innovation: most new technologies are combinations of existing ones [81,82]. Knots, in many respects, are exemplary combinatory tools, acting as binds that allow the invention and construction of composite technologies. Despite this, the role of knotting in early human behaviour has been largely overlooked. We argue that knotting catalysed combinatorial thinking, enabling the imagination and experimentation with various combinations of technological elements. This hastened the evolution of new technologies and contributed to a combinatorial growth of innovations in the deep human past. The globally shared and rather limited repertoire of knots represented in our dataset appears largely independent of ecological setting or socio-economic system. Furthermore, the very same knots are represented in the archaeological samples dating back thousands of years. We therefore suggest that some corpus of knots – perhaps consisting of the sheet bend, reef knot, cow hitch and overhand knot – likely has a prehistory that reaches back to be very beginnings of human string use, acting as technological catalysts ever since the first emergence of string.

The present methodology can be generalized to any object made from string (or similar interlaced materials), which could enable the comparison of 'topological fingerprints' of textiles, braids (e.g., ropes), basketry, and so on, presenting a vast array of potential future studies on the topic of ethnotopology. Presently, extending the method beyond two-strand knots results in a veritable explosion of possible Gauss code configurations, which may be impractical to solve manually (applying the method above, representing a three-strand knot would already require a total of 156 Gauss codes). Yet, by using more advanced computational tools, this process could be automated. Especially when combined with computer vision, such an application could take the topological fingerprint of any cordage pattern (e.g., textile, basket, braid, knot), matching it against a large dataset of other patterns. Although expanding this kind of topological 'DNA-matching' is left to be realized in future work, such methods could present a promising avenue for cross-cultural anthropological and archaeological research.

[2] Interestingly, the knots used by the Inka and Kanak for communicative purposes are highly similar: both used a slip knot (ABoK #529) and the overhand knot (ABoK #514).

6. Conclusion

This study highlights the profound role of knot-making in the cultural and technological evolution of human societies, a topic given surprisingly limited attention until now. By employing a novel combination of knot theory and computational string matching, we analysed a global sample of 332 knots from 83 ethnographically or archaeologically documented societies spanning ten millennia. Our analyses reveal a shared human heritage of knotting techniques, pointing towards a deep history of a staple repertoire of knots. Our findings suggest that certain fundamental knots, like the sheet bend, reef knot, cow hitch and overhand knot, have been key technological components across multiple epochs and locations, likely due to their functional reliability and ease of transmission over generations. In the ethnographic records, the sheet bend is an especially common find that can be traced in the archaeological record to over 10,000 years ago. Owing to the poor preservation of organic material, we may assume that it truly is an even older innovation. The persistence of some types of knots over millennia speaks to their integral role in daily life and their fitness to various practical needs.

While some societies portray higher levels of experimentation with knot structures, societies overall appear to have experimented less with practical knots than with, for instance, the more playful string figures [39]. This may suggest that a staple corpus of reliable knots has been good enough for the bulk of quotidian pre-industrial purposes, easy to accurately transmit through social learning, or that the failproof nature of knots has precluded experimentation. In other words, these knots appear to fall into a sweet spot between practical use and cognitive effort [62]. This insight has broader implications for understanding cultural and technological evolution, since it highlights how the degrees of freedom afforded by play or other non-functional domains (aesthetics, etc.) may act as cognitive catalysts that spur innovation [39,83,84].

Looking ahead, the methodological framework developed in this study offers exciting prospects for broader applications in the study of ancient and contemporary string technologies. By extending approach, which we call ethnotopology, future research could explore a wider array of string-based artifacts [39], potentially uncovering new insights into the cognitive, mathematical, and social dimensions of string manipulation as a human technology. With continued refinement of these analytical tools, there is considerable potential to deepen our understanding of cultural continuity, innovation, and the cognitive skills that have shaped human interaction with these kinds of material technologies.

Finally, we note that despite their ubiquity and cultural relevance, knots are relatively poorly documented in the ethnographic and archaeological records. Ours is the first systematic global review of knots as documented ethnographically and archaeologically. Yet without a doubt, swathes of relevant data exist that are not included here, and which remain entirely unanalysed. Museum archives worldwide contain thousands of knots that have not been given attention, nor do contemporary ethnographies routinely pay consideration to such vital technologies in sufficient detail. The methods presented here offer a straightforward way of formalizing those knots into Gauss code and matching them against a global dataset. Therefore, we see much potential in expanding this dataset in the future. Given the accelerating rates of cultural extinction [85] and the loss of traditional knowledge, as well as the poor preservation of organic cordage material in general, it is important to digitize, with some urgency, the limited evidence we have of knot-tying traditions worldwide.

Funding Statement

R.O.K. was supported by Research Council of Finland grant 347305. F.R. acknowledges funding from the Aarhus University Research Foundation grant 'PLAY|OBJECT|PLAY: The role of the early-age niche provisioning in technological innovation and adaptation' (AUFF-E-2021-9-4). M.A.M. and J.T.E. acknowledge funding from KONE Foundation grant 'Arkistotiedon käyttö ympäristöntutkimuksessa – pohjoisen sosioekologinen ympäristöhistoria työkaluna ympäristömuutosten ymmärtämiseen'. J.T.E. was also supported by funding under the European Union's Horizon 2020 Research and Innovation Programme, grant agreement no. 869471 (project CHARTER).

Data Accessibility

The dataset (including all Gauss codes and other documentation of knots) and the R code used for analysis and data visualisation are available on OSF. DOI: https://doi.org/10.17605/OSF.IO/2F96U

Competing Interests

We declare no competing interests.

References

1. Hardy K. 2008 Prehistoric string theory. How twisted fibres helped to shape the world. *Antiquity* **82**, 271–280.

2. Conard NJ, Rots V. 2024 Rope making in the Aurignacian of Central Europe more than 35,000 years ago. *Science Advances* **10**, eadh5217. (doi:10.1126/sciadv.adh5217)

3. Tylén K, Fusaroli R, Rojo S, Heimann K, Fay N, Johannsen NN, Riede F, Lombard M. 2020 The evolution of early symbolic behavior in Homo sapiens. *PNAS* **117**, 4578–4584. (doi:10.1073/pnas.1910880117)

4. Overmann KA, Wynn T. 2019 Materiality and Human Cognition. *Journal of Archaeological Method and Theory* **26**, 457–478. (doi:10.1007/s10816-018-9378-y)

5. Malafouris L. 2021 How does thinking relate to tool making? *Adaptive Behavior* **29**, 107–121. (doi:10.1177/1059712320950539)

6. Barham L. 2013 *From hand to handle: the first industrial revolution*. Oxford: Oxford University Press.

7. Mayer DEB-Y, Groman-Yaroslavski I, Bar-Yosef O, Hershkovitz I, Kampen-Hasday A, Vandermeersch B, Zaidner Y, Weinstein-Evron M. 2020 On holes and strings: Earliest displays of human adornment in the Middle Palaeolithic. *PLOS ONE* **15**, e0234924. (doi:10.1371/journal.pone.0234924)

8. Oswalt WH. 1976 *An Anthropological Analysis of Food-Getting Technology*. New York, NY: John Wiley & Sons.

9. Ashley CW. 1944 *The Ashley Book of Knots*. Doubleday.

10. Bar-Natan D, Morrison S. 2024 Knot Atlas. See http://katlas.math.toronto.edu/wiki/Main_Page (accessed on 19 January 2024).

11. Darcy IK. 2021 DNA Knots and Links. In *Encyclopedia of Knot Theory* (eds C Adams, E Flapan, A Henrich, L Kauffman, LD Ludwig, S Nelson), Routledge.

12. Adams C, Devadoss J, Elhamdadi M, Mashaghi A. 2020 Knot theory for proteins: Gauss codes, quandles and bondles. *J Math Chem* **58**, 1711–1736. (doi:10.1007/s10910-020-01151-0)

13. Kauffman LH, Lomonaco SJ. 2007 Quantum Computing and Quantum Topology. In *Mathematics of Quantum Computation and Quantum Technology*, Chapman and Hall/CRC.

14. Fienup-Riordan A. 2007 *Masterworks of Yup'ik Science and Survival: Yuungnaqpiallerput, the Way We Genuinely Live*. Anchorage Museum of History and Art.

15. Rice TT. 1957 *The Scythians*. London: Thames & Hudson.

16. Chen L. 2007 *The Complete Book of Chinese Knotting: A Compendium of Techniques and Variations*. Tuttle Publishing.

17. Ascher M, Ascher R. 2013 *Mathematics of the Incas: Code of the Quipu*. Courier Corporation.

18. Handy ESC. 1923 *The Native Culture in the Marquesas*. Honolulu, Hawaii, The Museum.

19. Bain G. 1973 *Celtic Art: The Methods of Construction*. Courier Corporation.

20. Davis C. 2000 *Celtic and Old Norse Designs*. Dover Publications.

21. Danino M. 2003 The Harappan heritage and the Aryan problem. *Man and environment* **28**, 21–32.

22. Day CL. 1967 *Quipus and Witches' Knots: The Role of the Knot in Primitive and Ancient*

Cultures. University Press of Kansas.

23. Hage JJ. 2008 Heraklas on Knots: Sixteen Surgical Nooses and Knots from the First Century A.D. *World Journal of Surgery* **32**, 648–655. (doi:10.1007/s00268-007-9359-x)

24. Russo C. 2019 *Hojojutsu: The Warrior's Art of the Rope*. Yoshin Ryu.

25. Buck PH. 1930 *Samoan Material Culture*. Honolulu, Hawaii: The Museum.

26. Buck PH. 1957 *Arts and Crafts of Hawaii*. Bishop Museum Press.

27. Turner JC, Van De Griend P. 1996 *History and Science of Knots*. World Scientific.

28. Graff R. 1964 Knots used by the Lapps. In *Lapponica*, H. Ohlssons Boktryckeri.

29. Itkonen TI. 1948 *Suomen lappalaiset vuoteen 1945. Osa 1*. Werner Söderström Osakeyhtiö.

30. Te Rangi Hīroa. 1926 The Maori craft of netting. *Transactions and Proceedings of the New Zealand Institute* **56**, 597–646.

31. Jennings JD. 1957 *Danger Cave*. University of Utah Press.

32. Haury EW (Emil W. 1950 *The Stratigraphy and Archaeology of Ventana Cave, Arizona*. University of Arizona Press.

33. Ambro RD. 1966 Two Fish Nets from Hidden Cave, Churchill County, Nevada. *Reports of the University of California Archaeological Survey*

34. Scanlon LA, Lobb A, Tehrani JJ, Kendal JR. 2019 Unknotting the interactive effects of learning processes on cultural evolutionary dynamics. *Evolutionary Human Sciences* **1**, e17. (doi:10.1017/ehs.2019.17)

35. Scanlon LA. 2019 *Cultural evolution of material knot diversity*. Durham University.

36. Muthukrishna M, Shulman BW, Vasilescu V, Henrich J. 2014 Sociality influences cultural complexity. *Proceedings of the Royal Society B: Biological Sciences* **281**, 20132511. (doi:10.1098/rspb.2013.2511)

37. Caldwell CA, Renner E, Atkinson M. 2018 Human Teaching and Cumulative Cultural Evolution. *Rev.Phil.Psych.* **9**, 751–770. (doi:10.1007/s13164-017-0346-3)

38. Derex M, Godelle B, Raymond M. 2013 Social learners require process information to outperform individual learners. *Evolution* **67**, 688–697. (doi:10.1111/j.1558-5646.2012.01804.x)

39. Kaaronen RO, Walsh MJ, Henrich AK, Wisher I, Miu E, Manninen MA, Eronen JT, Riede F. 2024 A global cross-cultural analysis of string figures reveals evidence of deep transmission and innovation. (doi:10.31219/osf.io/yxpg8)

40. Alfaro Giner C. 2010 Fishing nets in the ancient world: the historical and archaeological evidence. In *Ancient Nets and Fishing Gear* (eds T Bekker-Nielsen, D Bernal Casasola), pp. 55–81. Universidad de Cádiz, Servicio de Publicaciones; Aarhus University Press.

41. Schultze LS, Knight EC, Ziolkowski T. 1907 *In Namaland and the Kalahari*. Gustav Fischer.

42. Johnson I. 2021 Gauss Diagrams. In *Encyclopedia of Knot Theory* (eds C Adams, E Flapan, A Henrich, L Kauffman, LD Ludwig, S Nelson), Routledge.

43. Johnson I, Henrich A. 2017 *An Interactive Introduction to Knot Theory*. Courier Dover Publications.

44. Gauss CF. 1900 *Werke: Achter Band*. Springer Fachmedien Wiesbaden GMBH.

45. Lawrence ED. 2021 What Is a Tangle? In *Encyclopedia of Knot*

Theory (eds C Adams, E Flapan, A Henrich, L Kauffman, LD Ludwig, S Nelson), Routledge.

46. Van der Loo MP. 2014 The stringdist package for approximate string matching. *The R Journal* **6**, 111.

47. Kauffman L. 2021 Virtual Knot Theory. In *Encyclopedia of Knot Theory* (eds C Adams, E Flapan, A Henrich, L Kauffman, LD Ludwig, S Nelson), Routledge.

48. Matzig DN, Hussain ST, Riede F. 2021 Design Space Constraints and the Cultural Taxonomy of European Final Palaeolithic Large Tanged Points: A Comparison of Typological, Landmark-Based and Whole-Outline Geometric Morphometric Approaches. *Journal of Paleolithic Archaeology* **4**, 27. (doi:10.1007/s41982-021-00097-2)

49. Bekker-Nielsen T, Casasola DB. 2010 *Ancient nets and fishing gear: Proceedings of the International Workshop on 'Nets and Fishing Gear in Classical Antiquity: a first Approach'*. Servicio de Publicaciones de la Universidad de Cádiz.

50. Berihuete-Azorín M, Lozovskaya O, Herrero-Otal M, Huerta RP i. 2023 Fishing Nets and String at the Final Mesolithic and Early Neolithic Site of Zamostje 2, Sergiev Posad (Russia). *Open Archaeology* **9**. (doi:10.1515/opar-2022-0283)

51. Yu G, Lam TT-Y, Xu S, Li L, Jones B, Silverman J, Iwasaki WM, Xia Y, Huang R. 2023 ggtree: an R package for visualization of tree and annotation data. (doi:10.18129/B9.bioc.ggtree)

52. Warner C. 1996 Why knot? Some speculations on the earliest knots. In *History and science of knots* (eds JC Turner, P Van De Griend), pp. 19–30. World Scientific.

53. Stokes JFG, Sherman MA. 1994 String Figures from the Austral Islands. *Bulletin of the International String Figure Association* **1**, 69–150.

54. Lessa WA. 1959 Divining from Knots in the Carolines. *The Journal of the Polynesian Society* **68**, 188–204.

55. Manninen MA, Damlien H, Kleppe JI, Knutsson K, Murashkin A, Niemi AR, Rosenvinge CS, Persson P. 2021 First encounters in the north: cultural diversity and gene flow in Early Mesolithic Scandinavia. *Antiquity* **95**, 310–328. (doi:10.15184/aqy.2020.252)

56. Pälsi S. 1920 *Ein steinzeitlicher Moorfund bei Korpilahti im Kirchspiel Antrea, Län Viborg*. KF Puromiehen Kirjapaino O.-Y.

57. Nurminen K. 2020 Fish Bones and Fishing in Finland during the Stone Age. *Iskos* **23**.

58. Burov GM. 1966 Archaeological finds in old peat bogs of the Vychegda basin. *Soviet Archaeology* **1**, 155–173.

59. Feulner F. 2012 Evidence of fishing in the Satrup bog, Kr. Schleswig-Flensburg, Germany. *Quartär* **59**, 165–174. (doi:10.7485/QU59_7)

60. van de Griend P. 1994 *Inuit Knot Structures*. Matematisk Institut Aarhus Universitet.

61. Van de Griend P. 1996 Inuit knots. In *History and science of knots* (eds JC Turner, P Van De Griend), pp. 107–132. World Scientific.

62. Tran N-H, Waring T, Atmaca S, Beheim BA. 2021 Entropy trade-offs in artistic design: A case study of Tamil kolam. *Evolutionary Human Sciences* **3**, e23. (doi:10.1017/ehs.2021.14)

63. Kaaronen RO, Manninen MA, Eronen JT. 2023 Rules of thumb, from Holocene to Anthropocene. *Anthropocene Review*. **10**, 685–709. (doi:10.1177/20530196221149105)

64. Kaaronen RO, Manninen MA, Roe E, Hukkinen JI, Eronen JT. 2021 Lessons

for human survival in a world without ecological templates: what can we learn from small-scale societies? *Ecology and Society* **26**.

65. Henrich J, Henrich N. 2010 The evolution of cultural adaptations: Fijian food taboos protect against dangerous marine toxins. *Proceedings of the Royal Society B: Biological Sciences* **277**, 3715–3724.

66. Kluckhohn C, Hill WW, Kluckhohn LW. 1971 *Navaho Material Culture*. Belknap Press of Harvard University Press.

67. Vandendriessche E. 2015 *String figures as Mathematics? An Anthropological Approach to String Figure-Making in Oral Tradition Societies*. Springer.

68. Maclaren PIR. 1955 Netting Knots and Needles. *Man* **55**, 85–89. (doi:10.2307/2795064)

69. Blandford PW. 1986 *Netmaking*. Glasgow : Brown, Son & Ferguson.

70. Broadhurst MK, Sterling DJ, Millar RB. 2016 Confounding effects of knot orientation in penaeid trawls. *Fisheries Research* **179**, 124–130. (doi:10.1016/j.fishres.2016.02.020)

71. Brand CO, Mesoudi A, Smaldino PE. 2021 Analogy as a catalyst for cumulative cultural evolution. *Trends in Cognitive Sciences* **25**, 450–461. (doi:10.1016/j.tics.2021.03.002)

72. Locke LL. 1912 The Ancient Quipu, a Peruvian Knot Record. *American Anthropologist* **14**, 325–332.

73. Urton G. 2010 Recording measure(ment)s in the Inka khipu. In *The Archaeology of Measurement. Comprehending Heaven, Earth and Time in Ancient Societies* (eds I Morley, C Renfrew), pp. 54–68. Cambridge University Press.

74. Leenhardt M. 1930 *Notes d'ethnologie néo-calédonienne*. Travaux Et Mémoires De L'Institut D'ethnologie, Université De Paris. See https://ehrafworldcultures.yale.edu/cultures/op04/documents/001.

75. Cushing FH. 1892 Manual Concepts: A Study of the Influence of Hand-Usage on Culture-Growth. *American Anthropologist* **5**, 289–318.

76. Christensen A. 1996 The Peruvian Quipu. In *History and science of knots* (eds JC Turner, P Van De Griend), pp. 71–88. World Scientific.

77. Griaule M. 1931 Attaches et nøeuds Abyssins. *Journal des Africanistes* **1**, 27–42.

78. Chrisomalis S. 2020 *Reckonings: Numerals, Cognition, and History*. MIT Press.

79. Johannsen NN, Malafouris L, Renfrew C. 2010 Technological conceptualization: Cognition on the shoulders of history. In *The Cognitive Life of Things*, pp. 59–69. Mcdonald Institute for Archaeological Research.

80. Malafouris L. 2013 *How Things Shape the Mind*. MIT Press.

81. Arthur WB. 2009 *The Nature of Technology: What It Is and How It Evolves*. Simon and Schuster.

82. Koppl R, Gatti RC, Devereaux A, Fath BD, Herriot J, Hordijk W, Kauffman S, Ulanowicz RE, Valverde S. 2023 Explaining Technology. *Elements in Evolutionary Economics* (doi:10.1017/9781009386289)

83. Riede F, Johannsen NN, Högberg A, Nowell A, Lombard M. 2018 The role of play objects and object play in human cognitive evolution and innovation. *Evolutionary Anthropology: Issues, News, and Reviews* **27**, 46–59. (doi:10.1002/evan.21555)

84. Riede F, Lew-Levy S, Johannsen NN, Lavi N, Andersen MM. 2022 Toys as Teachers: A Cross-Cultural Analysis of Object Use and Enskillment in Hunter–Gatherer Societies. *J Archaeol Method Theory* (doi:10.1007/s10816-022-09593-3)

85. Zhang H, Mace R. 2021 Cultural extinction in evolutionary perspective. *Evolutionary Human Sciences* **3**. (doi:10.1017/ehs.2021.25)