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Research Article

The Ties That Bind: Computational, Cross-cultural Analyses of Knots Reveal Their Cultural Evolutionary History and Significance

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Abstract

Integral to the fabric of human technology, knots have shaped survival strategies since their first invention. 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 338 knots from 86 ethnographically or archaeologically documented societies over 12 millennia. Utilizing 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 and fibre technologies.

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Introduction

The use of materials like plant fibres, leather, rawhide, or sinew to twine, bind, or secure objects is an ancient human technology (Conard & Rots 2024; Hardy 2008). Whether employing a simple strip or utilizing twined or corded materials—collectively known as 'string'—this practice has long been fundamental to human technology and its innovation. While methods such as twisting, looping and splicing have been used to manipulate fibres, knotting is one of several techniques that can expand the functionality of string technology by allowing secure connections between different objects. As ties that bind, knots have in part contributed to 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. We propose that knot-making technologies not only had a functional purpose, but were 'tools of the mind' involving complex cognitive operations (Malafouris 2021; Overmann & Wynn 2019; Tylén *et al.* 2020), and the curation of knot-making knowledge has had deep cultural significance. By exploring the ethnographic and archaeological evidence of knot-making in the past, we intend to elucidate the cultural nuances involved within this technology.

Direct archaeological evidence of early knotting is scarce due to the perishable nature of organic materials. However, indirect evidence suggests that knot-making may have been requisite knowledge passed on through social learning as early as the Lower and Middle Palaeolithic. For example, the lashing of early dwellings and hafting of tools (Barham 2013) may have involved knotting, as lashing techniques commonly use a variety of hitches as a starting knot (Ashley 1944). The earliest strung beads and ornaments dating back to 120,000–160,000 years ago (Mayer *et al.* 2020) may also have involved knots, since securing the string (with a stopper knot or by tying it into a loop) would prevent the beads from falling off. Indeed, use-wear analysis has demonstrated that knots were likely used to bind shell beads onto string at Blombos Cave over 70,000 years ago (fig. 2C in Vanhaeren *et al.* 2013). In the more recent past, human mastery of knots has, in combination with other fibre-working techniques, catalysed the cultural evolution

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Box 1. Basic knot terminology

Stopper: an end knot that creates a bulkier mass at the end of the cord, preventing the cord from unravelling, 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 knot: 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

of a range of technologies, including textiles and garments, hafted and composite tools and weapons, nets, snares, transport technologies and ornaments. The human intrigue with knots has come a long way: today, thousands of knots are known (Ashley 1944; Bar-Natan & Morrison 2024), with knot theory extending its reach into domains such as DNA and protein modelling (Adams *et al.* 2020; Darcy 2021) as well as quantum computation (Kauffman & Lomonaco 2007).

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 industrialized world. Beyond scouts, climbers, sailors 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 which require extensive knowledge of diverse knot types and their uses. For example, to tie a seaworthy kayak securely with sinew is no simple task (Fienup-Riordan 2007, 90) and reindeer husbandry requires a considerable repertoire of binds and hitches (Rørslett & Graff 2022). 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 and collaboration, with elaborate, staged operational sequences. The Pazyryk rug—one of the oldest documented carpets woven around 400–500 BCE—was made using over a million knots (Rice 1957, 141), approximately 277 knots per square inch (Böhmer & Thompson 1991, 31). Ever since the first knots emerged, knot-tying has been an intrinsic part of daily life and an important 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 (Chen 2007; Day 1967). 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 (Ascher & Ascher 2013). In Marquesas, knots have been used as genealogical mnemonics, helping to memorize a literal social ‘network’ (Handy 1923, 342). Knots are also common ornaments, from Polynesian sennit (Handy 1923) and Japanese *Mizuhiki* to Celtic (Bain 1973), Norse (Davis 2000) and Chinese (Chen 2007) decorative knots. Ornamental carvings of knots can be found as early as *c.* 2500 BCE in Mohenjo-Daro (Danino 2003) and are ubiquitous in ancient Greek and Egyptian art (Day 1967). Knots are a common topic in folklore and mythology as well, the most famous Western example being the legend of the Gordian Knot (Day 1967). Knots were also key to ancient medicine (e.g. Hage 2008), since they are required in surgery and in the making of slings and tourniquets. Knots are even utilized in martial arts such as the Japanese Hojōjutsu (Russo 2019).

Knots thus have deep cultural significance well beyond their functional purposes. The emergence and transmission of knot-making behaviours has been discussed by ethnographers (Buck 1930; 1957; Graff 1964; Itkonen 1948; Te Rangi Hīroa 1926; Turner & Van De Griend 1996), archaeologists (Ambro 1966; Haury 1950; Jennings 1957, 230) and cultural evolution scientists (Caldwell *et al.* 2018; Derex *et al.* 2013; Muthukrishna *et al.* 2014; Scanlon 2019; Scanlon *et al.* 2019), with each emphasizing the importance of knots in shaping technological and cultural development. Yet systematic analyses of their cross-cultural transmission and evolution remain lacking. To date, it is not sufficiently known whether there are regional or chronological patterns in human knot-making, nor whether certain knot topologies or types of knots share a deep evolutionary history. Concomitantly, it has not been possible robustly to reconstruct the cultural evolutionary history of knot-tying. Altogether, systematic cross-cultural evolutionary studies of string technologies have been largely restricted to weaving (Buckley 2012; Buckley *et al.* 2024) and our previous study on string figures (Kaaronen *et al.* 2024).

To this end, utilizing the ethnographic and archaeological archives of Human Relations Area Files (HRAF), the present study aims to address this gap by conducting a first global analysis of knot-tying traditions, exploring patterns of cultural transmission and the evolutionary dynamics underlying knot usage across societies. To achieve this, we develop a methodology that combines formal mathematical knot theory and computational string matching. Transforming knotted strings into numeric strings affords an unambiguous mathematical representation of knot topologies. In turn, this facilitates rigorous downstream computational analysis and comparison of knots. Our ethnographic and archaeological corpus of 338 knots from 86 societies around the world spans approximately 12,000 years and allows us to investigate the repertoire of ancient knots

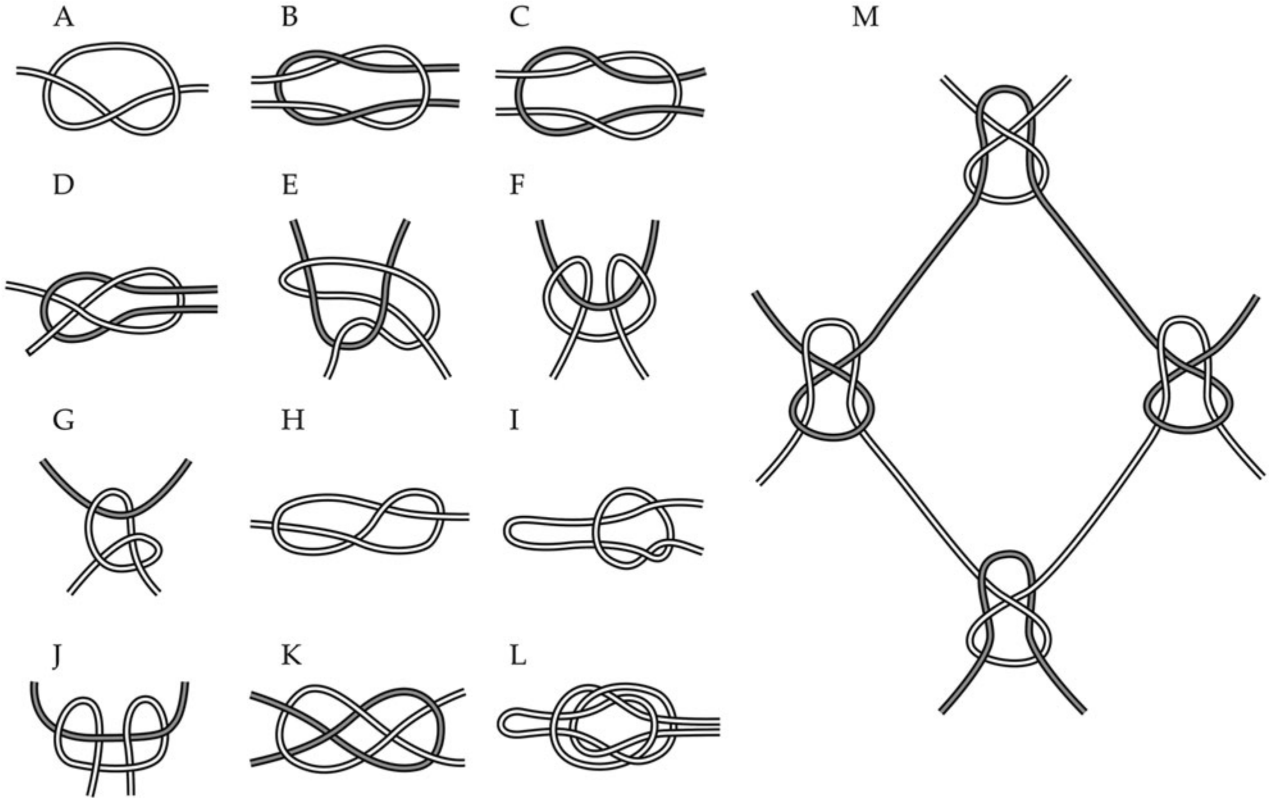


Figure 1. A collage of some common knots: (A) overhand knot; (B) reef knot (square knot); (C) granny knot; (D) sheet bend (weaver's knot); (E) sheet bend, alternative form (by pulling the bottom left string, the rightmost crossing moves to the centre, resulting in a knot isomorphic to 1D); (F) cow hitch (lark's head), netted form (hitched to another string); (G) palaphitic net knot (Alfaro Giner 2010) (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 (Schultze *et al.* 1907).

whose history, we assert, likely extends much deeper into the past than the 12 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 over time and across cultures. We consider potential factors affecting these historical patterns, such as cultural transmission, convergent evolution and task differentiation in the making of different knots in diverse cultural contexts.

While our focus is on knots, the methods developed here have broader applicability to other string technologies and objects made from interlaced materials. This opens new avenues for research into the cultural transmission of string technologies in material culture. Notably, we highlight how the proposed methodology could be applied to study any object made of string, allowing rapid cross-cultural analyses of string technologies across large datasets.

Materials and methods

Different knot types are often difficult to distinguish from one another simply by eye. Some knots may have a similar overall appearance (e.g. they may produce an identical shadow or visible topology) yet differ in minute details, as is the case with the square knot and the so-called granny knot shown in Figure 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, each resulting in a drastically different appearance, while retaining the same underlying topological structure. Knots can be reliably described using formal mathematical theory. Such theory has previously been applied in the study of knot-making traditions (Scanlon 2019), 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 (Kaaronen *et al.* 2024), we present a generalizable method that uses Gauss code to transform string technologies into numerical strings. We use this approach here to quantify 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

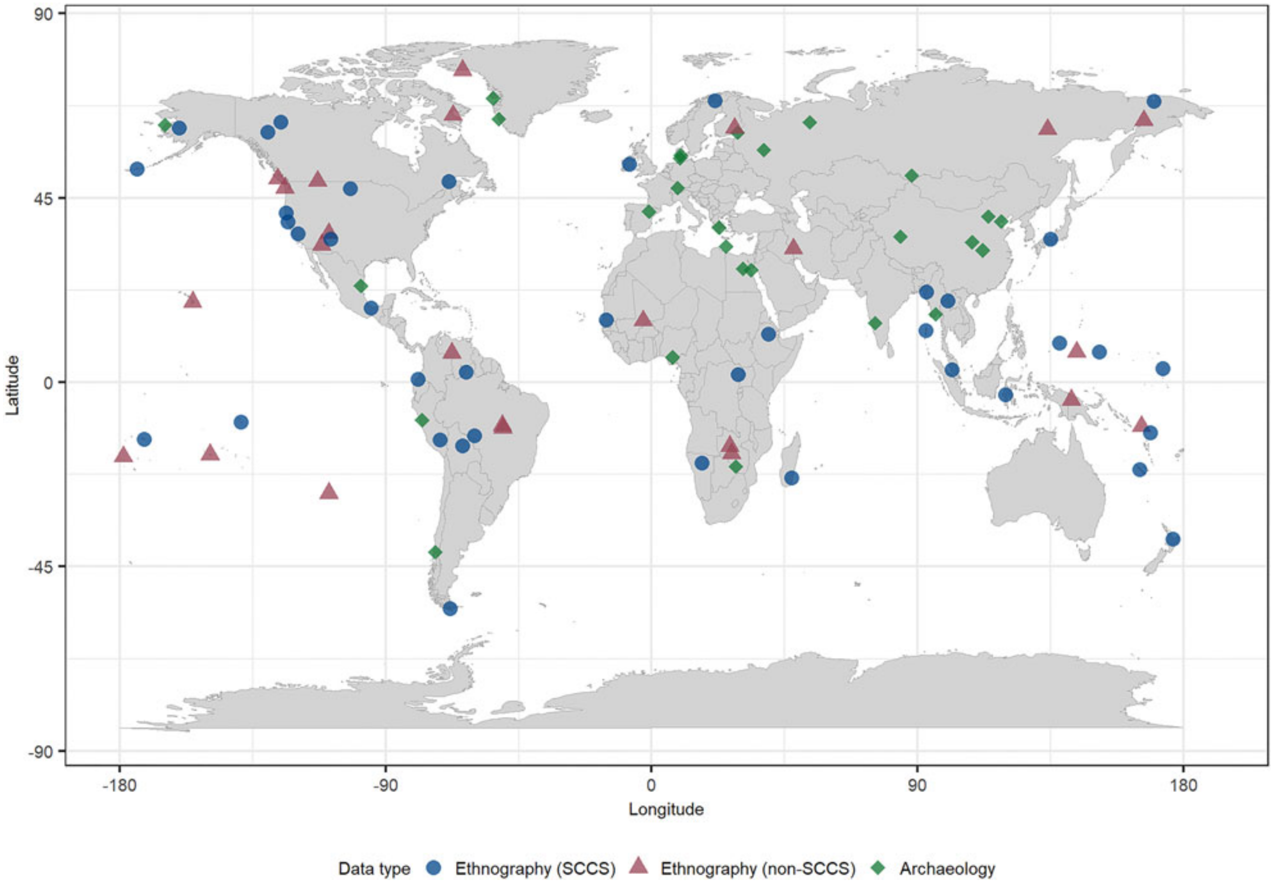


Figure 2. The geographic origins of the knots analysed. Knots are categorized based on whether they are documented in ethnographic or archaeological records. Ethnographic knots from societies in the Standard Cross-Cultural Sample are depicted as a separate category.

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 338 knots from 86 societies or archaeological traditions (Fig. 2). Of these, 94 knots are from archaeological finds and 244 from ethnographical descriptions; 199 of all knots are from HRAF. We did not include the knots from the *Ashley Book of Knots* (ABoK) (Ashley 1944) in our analysis. Knots in ABoK have already been formally analysed elsewhere (Scanlon 2019) 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 by visual evidence (illustrations, diagrams, photographs, etc.). The reasons for this are 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 twentieth century, and since then knot terminology has changed considerably.

Gauss coding

We use a variation of Gauss code, a standard method in knot theory (Gauss 1900; Johnson 2021; Johnson & Henrich 2017), 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 'knots' are almost never mathematical knots. 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' (Lawrence 2021). We developed a specific variation of Gauss code that is suitable for the analysis of practical knots and other string

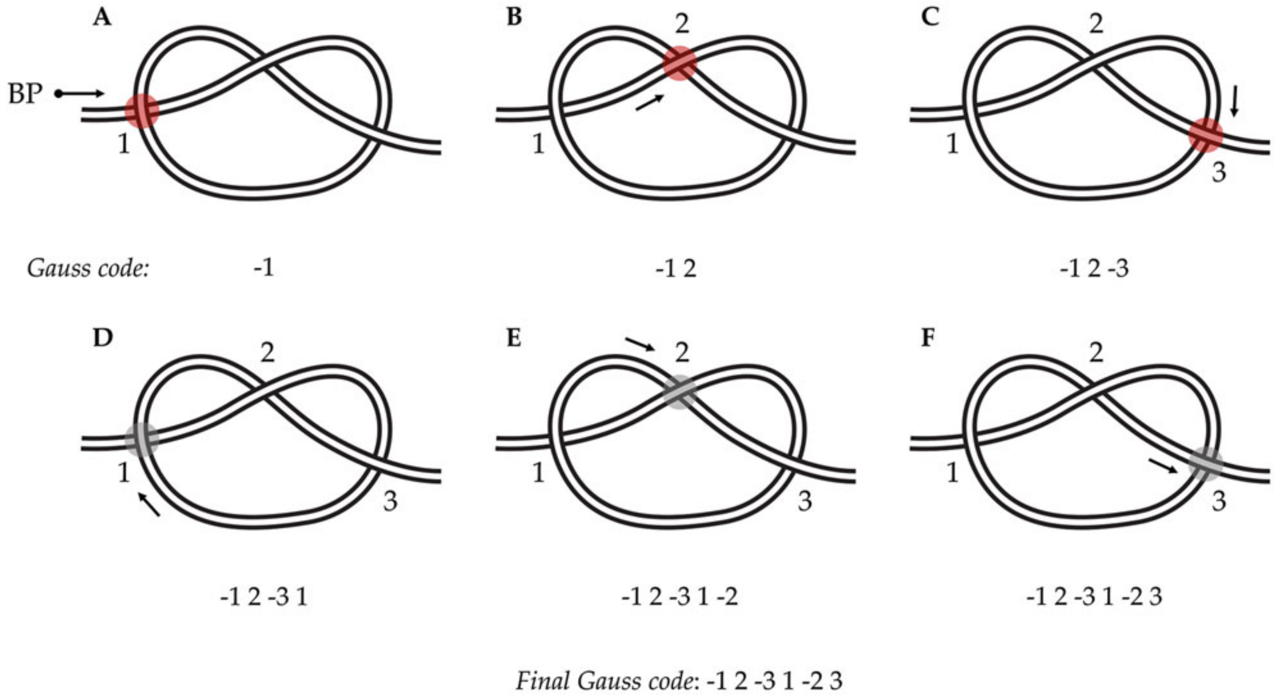


Figure 3. Gauss coding an overhand knot, the simplest of all knots.

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 method used here is best explained with a visual example, illustrated in Figure 3. When a knot is made from a single strand of string, Gauss coding can be done simply by picking one end of the knotted string (the basepoint, BP) and moving towards the other end. In Figure 3 panel A, the BP and orientation (clockwise) are marked with an arrow. Following the string, each encountered crossing is labelled sequentially with the natural number sequence (1, 2, 3, ..., *n*), where *n* is the number of unique crossings in the knot. When the same crossing is encountered for the second time, it is not relabelled. At panel D we encounter crossing 1 again, so we move on to the next crossing. If an unlabelled crossing were to appear later (this is true of many knots, but not of the overhand knot), we would continue labelling the newly encountered crossings in the order encountered. Once all crossings are labelled, we may start Gauss coding the knot. We start following the string from the same BP and orientation (panel A). This time, we record the value of the label encountered, with an important detail: when the section of string followed lies at the top layer of the crossing (overpass—using an analogy, imagine driving through the knot and going 'over a bridge'), it is recorded as a positive integer, and when it is on the bottom layer (underpass—'under a bridge'), it is recorded with a minus sign. In panel A, our string goes under crossing 1, so we record it as −1. In panel B, we encounter the overpass 2. These crossing values are sequentially appended into a string of integers (panels A to F), forming the Gauss code for the knot. In a knot, all crossings are always encountered twice (overpass and underpass). The Gauss code for the overhand knot, using the defined basepoint and orientation, is −1 2 −3 1 −2 3.

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 Figure 3 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 Kaaronen *et al.* 2024), 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.

We match strings using q-grams, a method we have previously used for the matching of string figures (Kaaronen *et al.* 2024). With q-grams, each Gauss code in Table 1 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 grey string in Figure 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

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

Table 2. Example: a q-gram profile of the overhand knot Gauss codes in Table 1.

2-gram	Count
'−1 2'	4
'2 −3'	4
'1 −2'	4
'−2 3'	4
'−3 1'	2
'3 −1'	2

a q-gram profile (Van der Loo 2014) for the knot, producing a matrix documenting the occurrence of each 2-gram in the knot's set of Gauss codes (Table 2). These q-gram profiles can then be compared using distance metrics. We use cosine distance (Van der Loo 2014) to compare pairs of q-gram profiles, which produces a convenient (dis)similarity metric in the range from 0 to 1 (Kaaronen *et al.* 2024). 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 Figure 3. Similar but not identical pairs of knots would have a lower cosine distance depending on their degree of (dis)similarity; 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- and two-stranded knots (2-tangles), since three-stranded knots are rare and would require additional methodological consideration (see Conclusion section). 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. This is because following 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.

Table 3 documents all the Gauss codes we obtain from the reef knot in Figure 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 in Table 3 by −1 produces the negative image, resulting in a total of 24 Gauss codes for any two-stranded knot. The same q-gram profile method as documented above can then be applied. 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: Kauffman 2021), which also must have a matching positive integer for each negative one.

In theory, any knot can be annotated in this way. In practice, some complex knots may be inconvenient to code and *caveats* arise. Gauss coding assumes we have 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: Chen 2007, 3). While such knots can be disentangled 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 sometimes be Gauss coded in more than one way (see Figure 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, recognizing 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 matrix is then visualized using hierarchical clustering. Similarly to our analyses of string figures (Kaaronen *et al.* 2024), we produce a dendrogram using complete linkage clustering. The complete linkage method creates various small

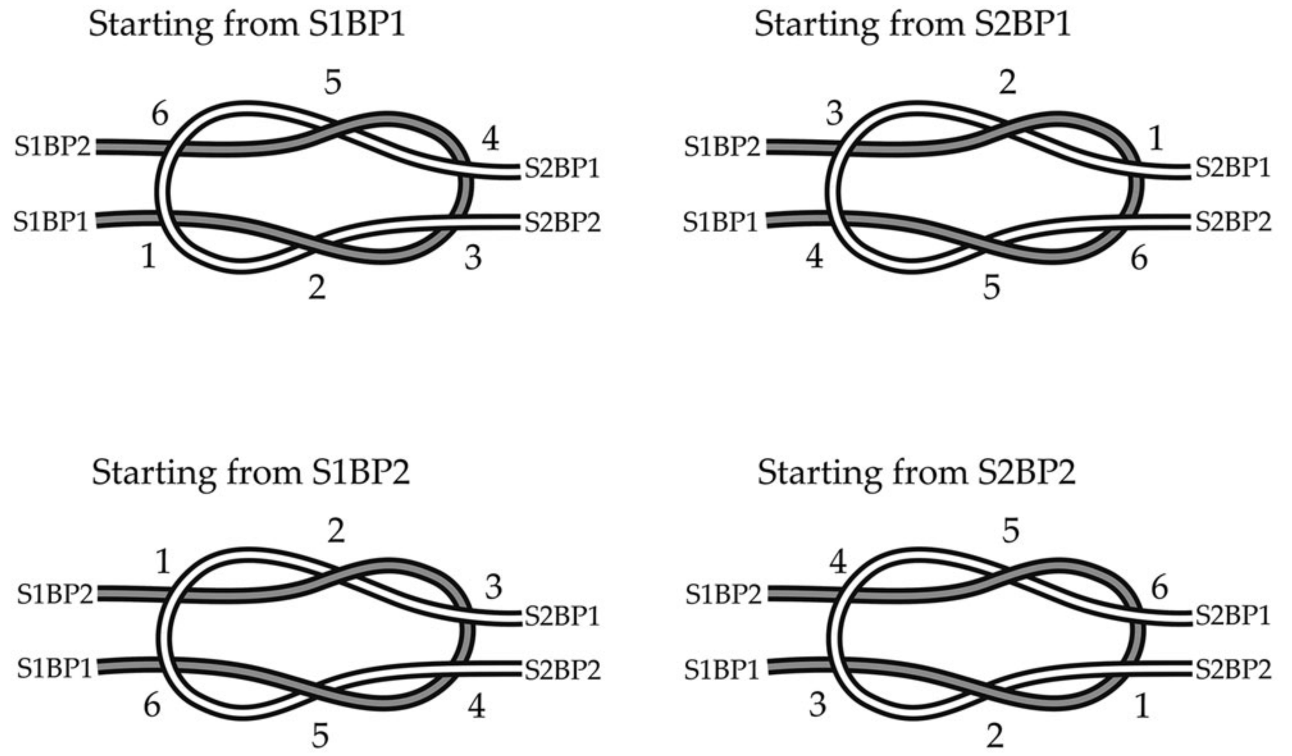


Figure 4. A reef knot Gauss coded in all possible configurations of basepoints and orientations. Starting from S1BP1, the knot is thus given three strings of Gauss code: the base code '−1 2 −3 −4 5 −6', and the two auxiliary codes '4 −5 6 1 −2 3', '3 −2 1 6 −5 4'. When the same logic is repeated for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

Table 3. 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

and discretized clusters with the assumption that an existing object represents each cluster (see table 1 in Matzig *et al.* 2021). This is suitable for the present purpose, since we may assume that each cluster is represented by a real knot, and we intend to visualize multiple groupings of structurally variable knots. This clustering method is particularly useful for visualizing knot data, since mutually identical knots will have a cosine distance of 0 and thus reliably cluster together. This readily visualizes how common and globally spread certain knots are. Similar but not quite identical knots (e.g. the reef knot and granny knot) will typically cluster near each other, enabling the rapid identification of look-alike knots.

Qualitative classification

We are not only interested in the structure of the knots, but also their function: the same knot may have variable uses in different cultural contexts. We classified a typology (Table 4) that accounts for both its immediate function—what class of knot it is—and its cultural context—what it was used for, recognizing that there are basic knots or repertoires of knots that are widely used to accomplish specific ranges of tasks, such as bushcraft activities like traditional hunting, trapping and fishing, or in livestock handling or the use of personal watercrafts, etc. 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.

Results

We identify 33 cross-culturally recurring knots in the dataset. The data also include a variety of idiosyncratic or complex knots that appear only in a single society. This

Table 4. 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**

illustrates how people around the world have used a set of staple knots to solve a variety of everyday problems. It simultaneously highlights how different cultures have experimented with more complex and unusual knots, innovated in response to specific cultural demands (see Discussion). Figure 5 presents a dendrogram where the names of the leaf nodes 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 adjacent clusters. In Figure 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 (clusters #402 and #1497; documented in 29 cultures), overhand knot (#514; 24 cultures), reef knot (#75 and #74; 23 cultures) and cow hitch (clusters #5; 20 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 (Kaaronen *et al.* 2024). 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. Figure 7 summarizes our dataset based on this classification. Since netting knots are especially common in our dataset, and are also of particular interest in archaeology (Bekker-Nielsen & Casasola 2010; Berihuete-Azorín *et al.* 2023), we plot in Figure 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, half-hitches (palaphitic knots: see Alfaro Giner 2010, 64), granny knots (INNU_1) and cow hitches, among others (Fig. 8)—over half (24 out of 42) of the fishing nets in our dataset use a variation of the sheet bend. This is a striking conformity that we discuss further below.

Discussion

Cultural transmission, task differentiation, and the deep past of knots

Our results show that humans across the world have made very similar knots, and that 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, cow hitch and clove 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 (in opposite directions, producing symmetrical form: Fig. 1B) (Warner 1996). Accordingly, previous research has speculated that knots like these would have been among the first knots humans tied (Warner 1996). 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. 1D–E), yet it is the most commonly recurring knot in our dataset. The sheet bend is especially common across Austronesian cultures, where it is used in making fishing nets (Buck 1930; 1957; Te Rangi Hīroa 1926). Given the evidence of other similar shared knowledge among Austronesian peoples—including string figures (Kaaronen *et al.* 2024; Stokes & Sherman 1994), sennit (Handy 1923) and knot divination practices (Lessa 1959)—it

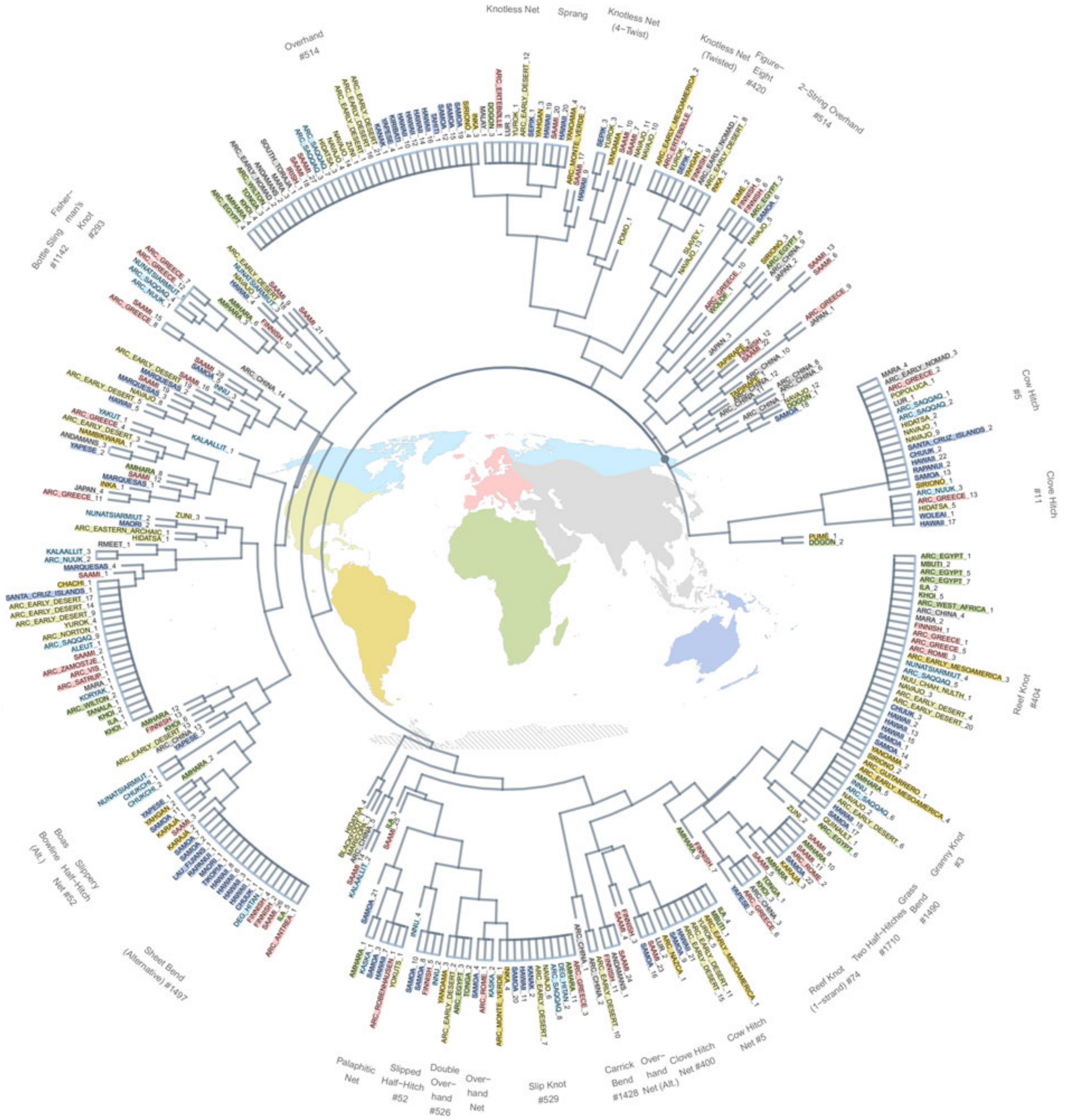


Figure 5. A phenetic tree (dendrogram) of knots produced with complete linkage clustering. Clusters at the outermost layer contain sets of identical knots and are highlighted with a bar. These clusters are named and numbered (based on ABoK) where possible. Clusters under the same branch contain structurally similar knots (e.g. the granny and reef knot). Knots from archaeological traditions are labelled with the prefix 'ARC_'. The ggtree (Yu *et al.* 2023) 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 5 is also available as a text-searchable pdf Supplementary file.)

is reasonable to assume that this indicates a strong pattern of cultural transmission by social learning across this region.

Sheet bend netting knots have a long history, reflecting their deep and perhaps shared origins across human societies. Our analysis highlights sheet bends as 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 10,522 cal. BP (Manninen *et al.* 2021), 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 (Nurminen 2020; Pälsi 1920). 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 bends in the northern European archaeological record, with these knots also found in nets from the Final Mesolithic to Early Neolithic bog sites at Zamostje-2 (Berihuete-Azorín *et al.* 2023), Vis-1 (Burov 1966) and Satrup (Feulner 2012). Whether or not these similar knots

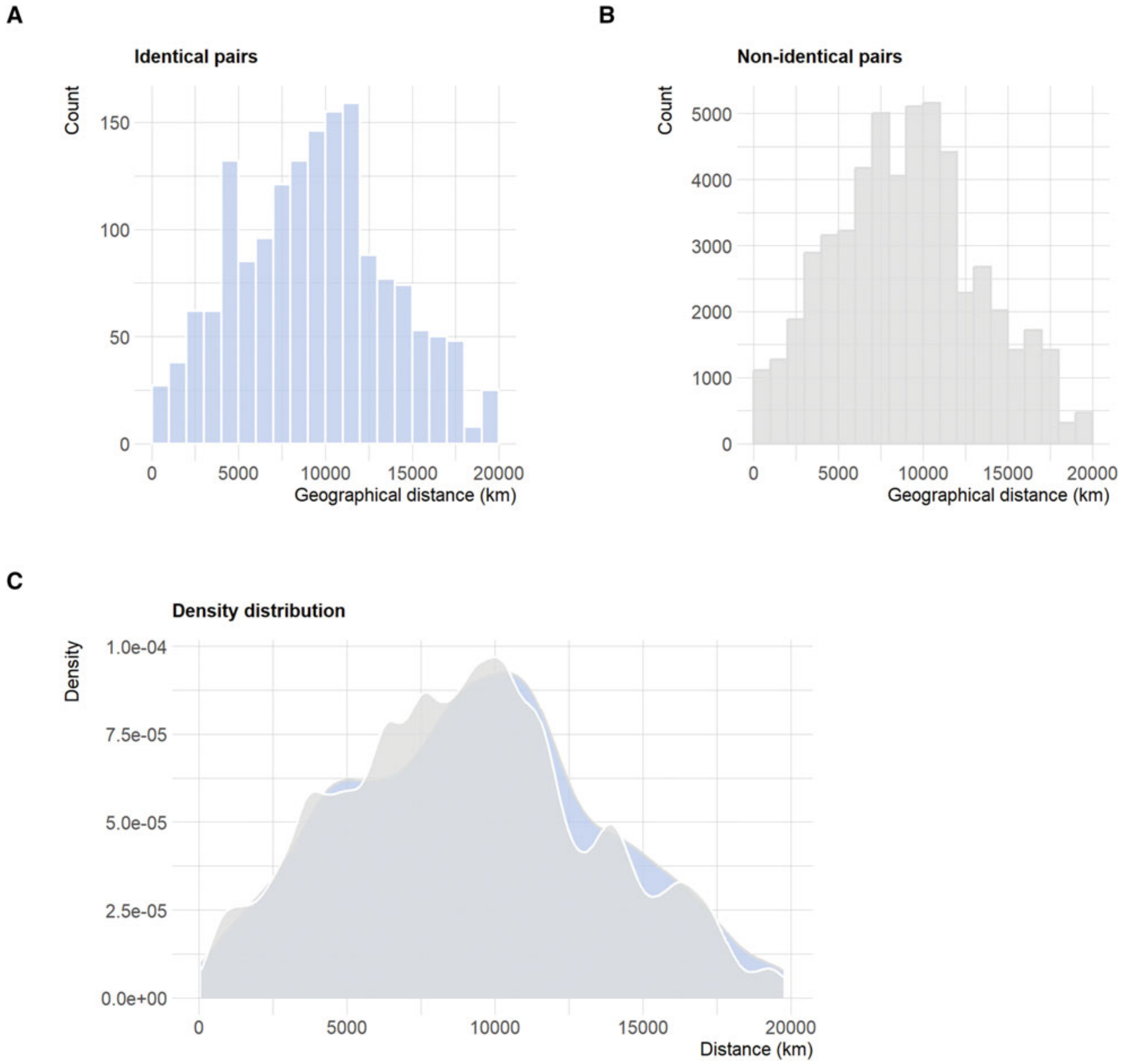
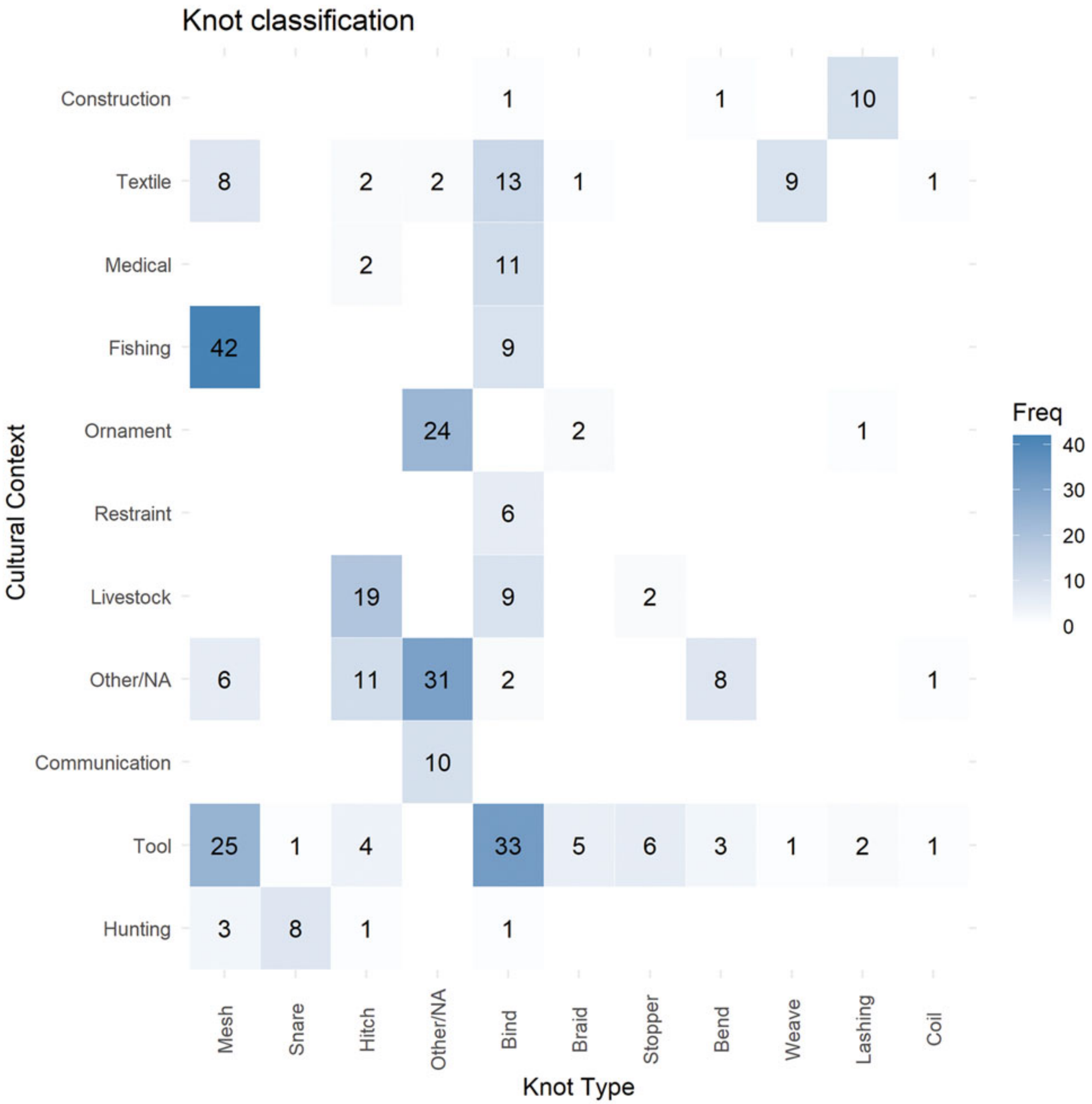


Figure 6. Histograms illustrate the geographical distribution of structurally identical (plot A) and non-identical (i.e. all other: plot B) pairs of knots. Within-society comparisons are excluded from this analysis. Plot C overlays the smoothed density distributions of histograms A and B, comparing the 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.

in archaeological finds reflect cultural transmission or convergent evolution is debatable. We postulate that the recurring sheet bend knots may signal shared knotting traditions among ancient northern European peoples, but further studies on the specific layout of these nets (and the orientation of the knots within) are required to validate this. Such analyses would be simple to conduct if more complete depictions of the net structures were available.

Some knots appear to be more geographically exclusive. For example, the so-called 'Boas bowline' knot (Van De Griend 1994; 1996) appears in our dataset only in societies residing in the Arctic, from Chukotka to Baffin Island and Greenland. The Boas bowline appears in two clusters in Figure 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. 1 F) is common in Mesoamerica and the southern regions of North America. The exclusive distribution of these knots within cultural regions suggests shared ancestry (Kaaronen *et al.* 2024), and 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



	Mesh	Snare	Hitch	Other/NA	Bind	Braid	Stopper	Bend	Weave	Lashing	Coil
Construction					1			1		10	
Textile	8		2	2	13	1			9		1
Medical			2		11						
Fishing	42				9						
Ornament				24		2				1	
Restraint					6						
Livestock			19		9		2				
Other/NA	6		11	31	2			8			1
Communication				10							
Tool	25	1	4		33	5	6	3	1	2	1
Hunting	3	8	1		1						

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 are largely due to the presence of archaeological data, where the original function of a knot is often not recoverable.

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 under load, yet is easy to untie), and despite its topological similarity to the sheet bend, our dataset includes no bowline knots (other than its Arctic 'Boas bowline' variant, and some other knots with bowline-like features, such as SAAMI_21 and ARC_EASTERN_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 (ABoK #1428), a secure yet more complex knot for connecting two ropes together, appears only twice in our dataset.

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

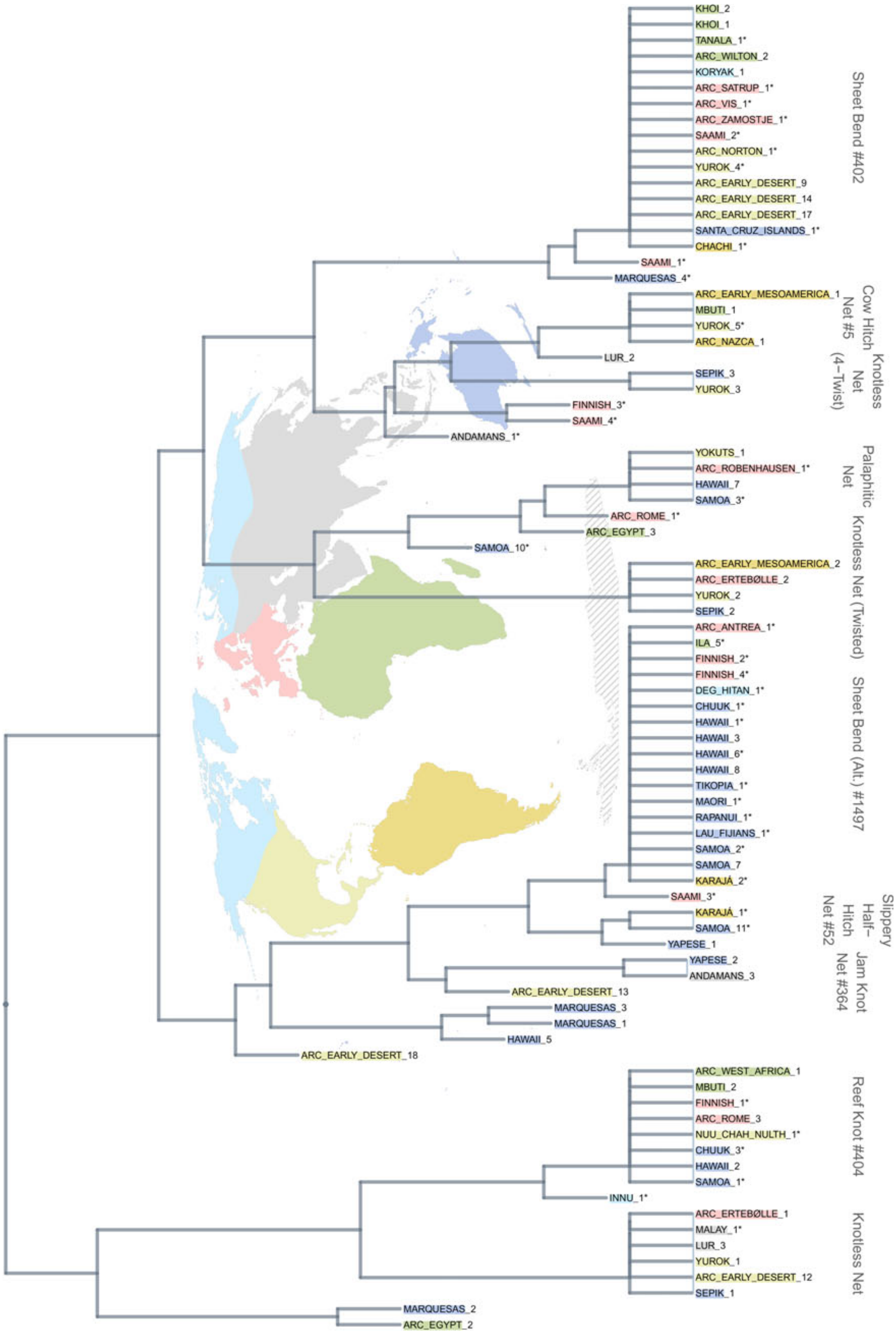


Figure 8. A dendrogram of mesh knots in our dataset. Fishing nets are marked with an asterisk (*). The sheet bend is the most common mesh knot and an especially common solution for tying fishing nets. The colour scheme is the same as in Figure 5. (Figure 8 is also available as a text-searchable pdf Supplementary file.)

(Tran *et al.* 2021). Since many traditional knots already fulfil their intended purposes elegantly and effectively, further exploration may offer only marginal improvements—in other words, known knots occupy local peaks in a rugged fitness landscape, where potential gains in utility are minor. Further, knots may be considered technologies under a strong failproof mandate, and the high costs of potential failure may have precluded exploration. This is especially true considering that added complexity may result in new possibilities for mistakes. The lack of transparent feedback further diminishes the potential for refinement: a knot may slip because it is poorly tied, but even a well-secured knot cannot prevent a cord from breaking, and the true cause of failure may often be left ambiguous.

In contrast, the state space of string figures (Kaaronen *et al.* 2024), 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 (Kaaronen *et al.* 2024), 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 that balance speed and ease of tying with their functional efficacy. Some ornamental knotting traditions, like Chinese knots (Chen 2007) 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.

The core repertoire of cross-culturally recurring knots in our dataset may reflect the task diversity for which they are suited. The sheet bend is particularly well suited for bends (joining two cords) and for tying secure and mendable mesh structures and is hence especially used in the context of netting and fishing (Fig. 8). The reef knot and overhand knot often act as all-purpose binds, with the latter also serving a useful purpose as a simple stopper knot. Knots like the cow hitch and clove hitch are commonly used as hitches around objects such as poles, also useful in lashing. A testament to the usefulness of these knots is that they are still today commonly considered 'essential knots' (Animated Knots 2024)—and they have been so for thousands of years. Notably, the reef knot and sheet bend represent the earliest knots in our dataset: the earliest documented reef knot is from Guitarrero Cave in the Peruvian Andes (dated 12,110–11,770 cal. BP by Jolie *et al.* 2011), and the earliest sheet bend is from the Antrea Net. The emergence of more idiosyncratic knots often coincides with more specialized subsistence practices. For instance, the unique repertoire of Saami reindeer hitching knots, some not documented elsewhere, may reflect specific reindeer-herding requirements (Rørslett & Graff 2022). Similarly, the development of intricate ornamental knots in Chinese traditions illustrates how aesthetic and symbolic factors can shape knot evolution (Chen 2007). Altogether, we suggest that a basic repertoire of multi-functional knots—a topological 'Swiss Army knife', capable of accomplishing a broad range of basic tasks—may underpin the commonalities observed across cultures. In contrast, the evolution of more specialized knots likely reflects past adaptations to more specific cultural demands.

Cognitive and cultural adaptations and ethnomathematics

Our data suggest 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 yet 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 accidentally to tie a granny knot when attempting a reef knot (Van De Griend 1994, 14). 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 (Van De Griend 1994, 14). 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 (Scanlon *et al.* 2019). 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 (Scanlon *et al.* 2019). Yet in our sample the exact opposite is the case. We document the reef knot in 23 cultures and the granny knot in only 8 (Fig. 5). Evidently, people around the world have knowingly preferred the secure reef knot over the insecure 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 (Kluckhohn *et al.* 1971, 232):

> 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].'

A recent experimental study has indicated that individuals without prior knotting experience tend to have poor intuition when judging the strength or physical behaviour of knots (Croom & Firestone 2024). Given that our data suggest a preference for secure knots, we might infer that experienced string users have a refined cognitive ability to assess knots and/or that cumulative cultural knowledge can surpass individual cognition. Through cultural selection, more effective knots may be retained and transmitted over generations, regardless of individuals' initial intuitions (for similar perspectives on how cultures can 'outsmart' individuals, see Henrich 2015).

Previously, we have suggested that expertise in string technologies may be considered ethnomathematical knowledge (Kaaronen *et al.* 2024; see also Vandendriessche 2015). String artifacts may be products of a distinctly human 'ethnotopological' way of thinking (Kaaronen *et al.* 2024). 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 alternate rows are not only mirror images, but also the 'front' and 'back' version (Maclaren 1955) 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 (Blandford 1986). In a fishing net, knot orientations also affect hydrodynamics, altering how a net performs in flowing water (Broadhurst *et al.* 2016). 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 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 (Maclaren 1955; Te Rangi Hīroa 1926), providing clues as to their evolutionary histories and their cultural transmission over generations. 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 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 (Brand *et al.* 2021), it also affords many other quantitative and communicative features. Of these, the Inka *quipu* (khipu) 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 (Ascher & Ascher 2013; Locke 1912; Urton 2010). However, the case of the *quipu* is not entirely unique. For example, the Kanak of New Caledonia have used similar[2] knots as means to transmit messages (Leenhardt 1930, 334–5), and the Zuni of the North American Southwest have used a base-10 positional knot system for counting and record keeping (Christensen 1996; Cushing 1892). Knots were also used for administrative records in Zhou dynasty China (Chen 2007, 9), and the Amhara of Highland Ethiopia have used overhand knots to count grain units for taxation (Griaule 1931).

Consequently, knot-making may have been a catalyst for mathematical and formal thinking in various loci (see also Kaaronen *et al.* 2024), and knots may be considered exemplary 'cognitive technologies' (Chrisomalis 2020)—tools that enter into a recursive relationship with cognition and so affect both the hardware and software of human thinking (Johannsen *et al.* 2010; Malafouris 2013). Particularly interesting is the role of knots as catalysts of a combinatorial explosion in human material culture cognition. Research in technological evolution has highlighted how recombination is essential for innovation: most new technologies are combinations of existing ones (Arthur 2009; Koppl *et al.* 2023). 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 prehistoric human behaviour has been largely overlooked. We argue that knotting, alongside other important binding techniques (lashing, adhesives, etc.), has catalysed combinatorial thinking, enabling the imagination and experimentation with various combinations of technological elements. This has contributed to the evolution of new technologies and contributed to a combinatorial growth of innovations. 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 record dating back thousands of years. We therefore suggest that some multifunctional corpus of knots—perhaps consisting of the sheet bend, reef knot, cow hitch, clove hitch and overhand knot—may have a deep prehistory, acting as technological catalysts over millennia.

Conclusion

This study highlights the important role of knot-making in cultural and technological evolution in 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 338 knots from 86 ethnographically or archaeologically documented societies spanning 12 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, clove hitch and overhand knot, have been important 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 and reef knot are especially common finds 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 they are even older than suggested by current archaeological evidence. 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 than others, societies overall appear to have experimented less with practical knots than with, for instance, the more playful string figures (Kaaronen *et al.* 2024). This suggests that a staple multi-purpose corpus of reliable knots has been good enough for the bulk of quotidian pre-industrial purposes, easy to transmit accurately through social learning, or that the failproof nature of knots has precluded experimentation. In other words, this suite of knots appears to fall into a sweet spot between practical efficacy and cognitive effort (Tran *et al.* 2021). 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 may act as cognitive catalysts that spur innovation (Kaaronen *et al.* 2024; Riede *et al.* 2018; 2022).

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 we call 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, AI, or machine learning, 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. 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 emphasize that knots are poorly documented in the ethnographic and archaeological records, despite their evident ubiquity and cultural relevance. Ours is the first systematic global review of knots as documented ethnographically and archaeologically. Presently, the main hindrance for ethnotopology research is the lack of accessible and digitized data. Yet, without a doubt, swathes of relevant data exist, especially in museum archives. The methods presented here offer a ready way of formalizing these knots into Gauss codes and matching them against a global dataset. If more complete 3-D models or 2-D diagrams of knotted and interlaced materials were available or crowdsourced, it would be convenient to use them in large-scale studies to infer cultural transmission histories and cultural evolutionary trajectories. We therefore propose a call to action for museums and researchers to digitize models of string patterns. Given the accelerating rates of cultural extinction (Zhang & Mace 2021) and the loss of traditional knowledge worldwide, as well as the poor preservation of organic cordage material in general, it is important to analyse, with some urgency, the limited evidence we have of knot-tying traditions at the global scale.

Supplementary material and data accessibility. Figures 5 and 8 are available as text-searchable pdf files at https://doi.org/10.1017/S0959774325000071

The dataset (including all Gauss codes and other documentation of knots) and the R code used for analysis and data visualization are available on OSF: https://doi.org/10.17605/OSF.IO/NJ423

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Notes

1. Note that taboos have been widely associated with practical functions, and they can often be considered precautionary cultural adaptations (Henrich & Henrich 2010; Kaaronen *et al.* 2021; 2023).

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).

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