9. J. Farquhar, J. Savarino, S. Airieau, M. H. Thiemens, *J. Geophys. Res.* **106**, 32829 (2001).
10. J. Farquhar *et al.*, *Science* **298**, 2369 (2002).
11. J. Farquhar, J. Savarino, T. L. Jackson, M. H. Thiemens, *Nature* **404**, 50 (2000).
12. X. Gao, M. H. Thiemens, *Geochim. Cosmochim. Acta* **57**, 3159 (1993).
13. X. Gao, M. H. Thiemens, *Geochim. Cosmochim. Acta* **57**, 3171 (1993).
14. Sulfide extractions were done by using the procedure described in (*13*); also see online Materials and Methods for more details. The typical errors of $\delta^{33}S$, $\delta^{34}S$, and $\delta^{36}S$ measurements are 0.010, 0.010, and 0.200 (in ‰), respectively.
15. We calculated ^{33}S and ^{36}S enrichment with the following equation: $\Delta^{33}S = \delta^{33}S - 1000[(1 + \delta^{34}S/1000)^{0.515} - 1]$ and $\Delta^{36}S = \delta^{36}S - 1000[(1 + \delta^{34}S/1000)^{1.91} - 1]$.
16. J. Farquhar, T. L. Jackson, M. H. Thiemens, *Geochim. Cosmochim. Acta* **64**, 1819 (2000).
17. M. F. Miller *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **99**, 10988 (2002).
18. C. E. Rees, H. G. Thode, *Geochim. Cosmochim. Acta* **41**, 1679 (1977).
19. X. Gao, M. H. Thiemens, *Geochim. Cosmochim. Acta* **55**, 2671 (1991).
20. Y. N. Chin, C. Henkel, J. B. Whiteoak, N. Langer, E. B. Churchwell, *Astron. Astrophys.* **305**, 960 (1996).
21. S. E. Woosley, A. Heger, T. A. Weaver, *Rev. Mod. Phys.* **74**, 1015 (2002).
22. R. Mauersberger, U. Ott, C. Henkel, J. Cernicharo, R. Gallino, *Astron. Astrophys.* **426**, 219 (2004).
23. S. E. Woosley, T. A. Weaver, *Astrophys. J. Suppl. Ser.* **101**, 181 (1995).
24. J. Farquhar, M. H. Thiemens, T. Jackson, *Science* **280**, 1580 (1998).
25. J. Farquhar, H. Bao, M. Thiemens, *Science* **289**, 756 (2000).
26. G. W. Cooper, M. H. Thiemens, T. L. Jackson, S. Chang, *Science* **277**, 1072 (1997).
27. J. J. Colman, X. Xu, M. H. Thiemens, W. C. Trogler, *Science* **273**, 774 (1996).
28. As a result of its small abundance, $\delta^{36}S$ is sensitive to contaminations at any stage from chemical extraction or gas chromatography or during measurements. The reported error on $\delta^{36}S$ is only measurement error; the actual uncertainty due to contamination might be higher.
29. M. A. Pasek *et al.*, *Icarus* **175**, 1 (2005).
30. J. W. Larimer, M. Bartholomay, *Geochim. Cosmochim. Acta* **43**, 1455 (1979).
31. K. Lodders, B. Fegley, *Earth Planet. Sci. Lett.* **117**, 125 (1993).
32. A. N. Krot, B. Fegley, K. Lodders, H. Palme, in *Protostars and Planets IV*, V. Mannings, A. P. Boss, S. S. Russell, Eds. (Univ. of Arizona, Tucson, AZ, 2000), pp. 1019–1054.
33. H. Nakano, A. Kouchi, S. Tachibana, A. Tsuchiyama, *Astrophys. J.* **592**, 1252 (2003).
34. P. Ramdohr, *Meteoritics* **7**, 565 (1972).
35. F. H. Shu, H. Shang, T. Lee, *Science* **271**, 1545 (1996).
36. F. H. Shu, H. Shang, A. E. Glassgold, T. Lee, *Science* **277**, 1475 (1997).
37. L. Grossman, *Geochim. Cosmochim. Acta* **36**, 597 (1972).
38. NASA Cosmochemistry program is gratefully acknowledged for support of this research.

Supporting Online Material
www.sciencemag.org/cgi/content/full/309/5737/1062/DC1
Material and Methods
Table S1
References and Notes

30 March 2005; accepted 12 July 2005
10.1126/science.1112954

Khipu Accounting in Ancient Peru

Gary Urton and Carrie J. Brezine

Khipu are knotted-string devices that were used for bureaucratic recording and communication in the Inka Empire. We recently undertook a computer analysis of 21 khipu from the Inka administrative center of Puruchuco, on the central coast of Peru. Results indicate that this khipu archive exemplifies the way in which census and tribute data were synthesized, manipulated, and transferred between different accounting levels in the Inka administrative system.

Tribute in the Inka state was levied in the form of a labor tax. Each "taxpayer" (state laborer) was required to work a specified number of days each year on state projects. Using data recorded in khipu (knotted-string devices used for bureaucratic recording and communication), Inka accountants assessed tribute levels and assigned tasks to different numbers of local workers. At the lowest, local level of the administrative hierarchy, tributaries were grouped into five accounting units of 10 members each. One member of each of these groups of 10 would have served as Chunka Kamayoq ("organizer of 10"). Five such groupings would make a unit of 50 tribute payers, under the authority of a Pichqa-Chunka Kuraka ("lord of 50"). Two groups of 50 would be combined into a unit of 100 tributaries led by a Pachaka Kuraka ("lord of 100") and so on up the hierarchy.

Near the top of the decimal administrative hierarchy were the heads of the approximately 80 provinces, the officials of which were called T'oqrikoq. Each provincial official was under the direction of the appropriate Lord of the Four Quarters; these four lords served directly under the Inka king in Cusco. The governor of each province was required to keep a copy of khipu accounts so that "no deception could be practiced by either the Indian tribute payers or the official collectors" (*1*).

Department of Anthropology, Harvard University, Cambridge, MA 02138, USA.

A primary question is how did information move between adjacent levels of this hierarchical administration? The instructions of higher-level officials for lower-level ones would have moved, via khipu, from the top of the hierarchy down. This information would be partitive in nature; for instance, assignments made to 1000 tribute payers would be broken down into two groups of 500, each of which would be decomposed into five groups of 100, and so on. In the reverse direction, local accountants would pass data regarding accomplished tasks upward through the hierarchy. In that direction, information at each level would represent the summation of accounts from the level immediately below. These accumulating data would eventually arrive in the hands of the Cusco accountants, where the highest level of accounting went on. Here we present an analysis of a set of khipu from Puruchuco that are linked hierarchically in such a relationship of summation and partition.

The archaeological site of Puruchuco is located on the south bank of the Rimac River, about 11.5 km northeast of the center of Lima, within the present-day district of Ate. Puruchuco is a roughly rectangular compound with high surrounding walls made of tapia (pounded adobe) construction. Around and in some cases abutted to the palace of Puruchuco were several smaller constructions. The cache of khipu was found under the floor of one of the smaller attached buildings. From its location, Mackey surmised that this building was the house of a khipu-keeper (khipukamayuq) who served the lord of the palace (*2*). Field notes from the day on which the khipu were discovered state that they were found inside a semi-ovoid urn covered by a small gourd. There were 21 khipu and several loose pendant strings (*3*).

What we term the Puruchuco "accounting hierarchy" pertains to 7 of the 21 khipu samples found together in the urn. Though not included in this analysis, several other khipu may provide supporting documentation to these seven. The seven khipu are related in a hierarchical arrangement of three interconnected levels, designated levels I, II, and III, as shown in Fig. 1. Two of the seven khipu (UR63 and UR73) were on level I, the base; three khipu were on the second level [UR64, UR68, and 9 (*4*)]; and two (UR67 and UR66) were on level III.

The two samples at the top of the hierarchy, UR66 and UR67, were rolled up together into a single bundle. These two khipu bear identical numerical values and string colors that seem to be a subtle transformation from one to the other.

There are two principal aspects of the Puruchuco accounting hierarchy. First, khipu on the same level match or closely match: They display identical or similar numerical sequences and color patterning. This, we argue, was the checks-and-balances aspect of the accounting hierarchy. Second, values on khipu sum upward and are subdivided downward: The numerical values of certain groupings of strings (to be defined below) on the two khipu on level I sum to values tied onto certain groupings of strings on the three khipu on level II, and the numerical values of certain groupings of strings on the three khipu on level II sum to the values on the two khipu on level III. Or, moving down the hierarchy, values on strings at higher levels are partitioned among groupings of strings on the next lowest level.

Through cord color and spacing, each of the seven khipu is organized into different

numbers of subunits. Khipu on level I decompose into six subunits; those on level II contain three subunits (plus what we call "introductory segments"); and the two khipu on level III have only one unit (plus introductory segments). Inside these subunits, the strings are further subdivided by a combination of spacing between strings and/or by the repetition of color patterning in groups of strings. The general color pattern is a four-string seriation or sequence of colors (such as dark brown, medium brown, light brown, and white) repeated multiple times (*5*, *6*). The numerical values of the cords vary in magnitude in accordance with the color, with the four strings of each color-seriated set generally increasing in size through the sequence.

An example of summation upward, between UR68 on level I and UR63 on level II, is given in Fig. 2. UR63 is organized by spacing and color seriation into six pendant string groupings, labeled a to f. The number of strings in each group is shown in brackets at the bottom of the columns. The six columns comprise (i) three sets of ($5 \times 4 =$) 20 strings organized into five groups of four color-seriated strings; (ii) two sets of ($3 \times 4 + 2 \times 3 =$) 18 color-seriated strings; and (iii) one set of ($3 \times 4 + 3 =$) 15 color-seriated strings. The meandering dotted lines at the tops and bottoms of the columns of UR63 in Fig. 2 show how this sample is to be reassembled into its proper linear arrangement. The numerical values of string groupings in UR63 sum to values recorded on the middle of the three subunits of UR68. The color-seriated strings of UR63 are aligned across the six segments, and these groupings are aligned with the similarly color-seriated grouping of ($5 \times 4 =$) 20 strings in the central subdivision (strings 34 to 53) of khipu UR68. Summing across the aligned strings of UR63 results in totals equal or close to those recorded on the depicted section of UR068. The values knotted into the cords of UR68 are reported on the right; any number between parentheses immediately to the left of these is the actual sum of values on the strings of UR63 at that position. The parenthetical numbers represent values that should have been recorded if the relationship between UR63 and UR68 was a matter of strict addition. The presence of several close, rather than exact, matches suggests that there was some degree of flexibility allowable in the accounting relationship between these two levels.

Continuing the summing upward, we next consider khipu UR68 (level II) and UR67 (level III). Their relationship is illustrated in Fig. 3. UR68 is disassembled into its three color-seriated subdivisions (labeled A to C), which are shown aligned with the similarly color-seriated string groupings of UR67. Figure 3 shows 20 strings in all subunits.

The summations between UR68 and UR67 are more exact than those between UR63 and UR68. Setting aside the broken string in UR67, the values diverge in only two instances, and in each case the discrepancies are small: 2904 instead of 2908 and 161 instead of 162. The variance present in the connection between levels I and II has been considerably reduced between levels II and III.

Pendants between dotted lines in Fig. 1 are implicated in the summation/partition relationship. The pendants on level III outside of the dotted lines, and those to the left of the dotted lines that protrude from the tops of the khipu on level II, form introductory segments. The dotted lines in Fig. 1 encompass all the pendants on level I khipu but only the middle subunit of level II khipu. That is, complete summation of level I khipu accounts for only a portion of the values recorded on khipu on level II. The other values on level II khipu are not accounted for by the currently known level I khipu UR63 and UR73. There may have been four additional level I khipu, with the information for these two additional subunits on level II. One pair would have summed to the leftmost subunits on level II, whereas the other would have produced sums recorded on

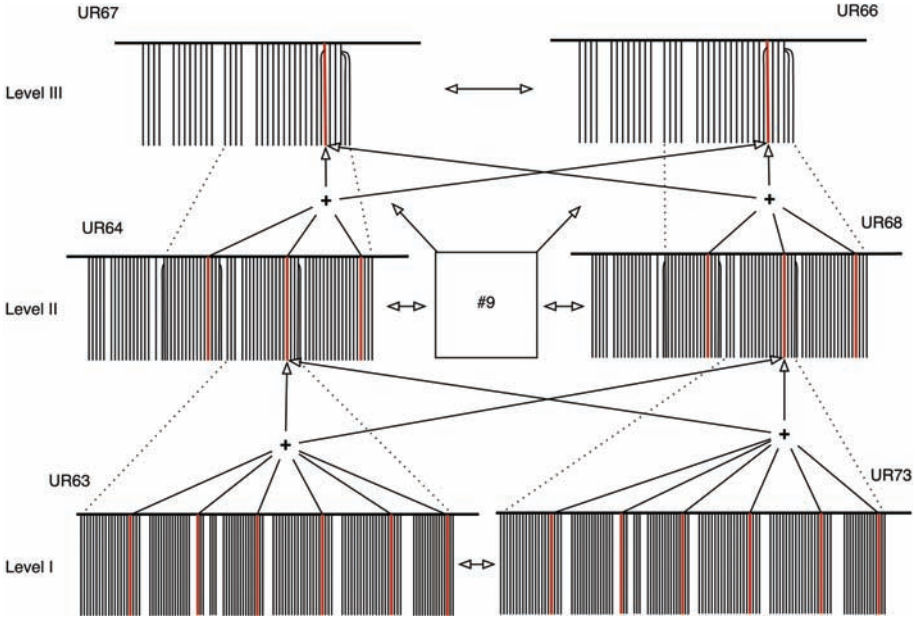

Fig. 1. The accounting hierarchy from the archive of Puruchuco.

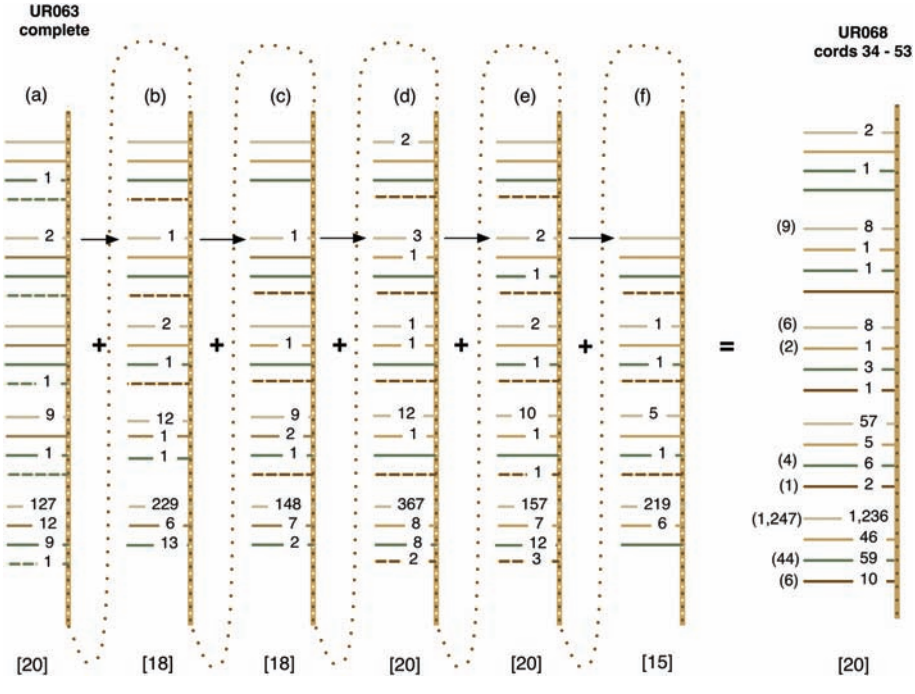

Fig. 2. Numerical and color correlations between khipu UR63 and the central section of UR68.

the right subunits. Except for the introductory segments, all strings on level III are involved in the summation relationship.

It appears that the original structure of the Puruchuco accounting hierarchy contained six paired khipu on level I, whose values were summed to produce those on the three subunits of the three khipu on level II, whose subunits in turn were summed and recorded on the two khipu on level III. Information was either being funneled and synthesized upward or subdivided and distributed downward among the three levels of khipu.

We assume that the Puruchuco accounting hierarchy was a set of records for use both within and outside the administrative center. Khipu on level III could represent either a set of instructions issued to the lord of Puruchuco from the provincial governor or reports on local Puruchuco resources to be sent to the provincial governor. In either of these scenarios, one of the requirements would have been that the khipu bear an indication of their destination or origination. If numerous khipu were coming into a central archive for storage or were being dispersed from that archive to disparate places, it would have been helpful, if not essential, to have place identifiers encoded within each khipu. We suggest that the introductory segments on level II and III khipu represented just such identity labels.

The numerical values knotted onto strings within the introductory segments on level II and III khipu all contain arrangements of just three figure-eight knots tied onto three separate strings. Figure-eight knots on khipu normally signify the numerical value one. We hypothesize that the arrangement of three figure-eight knots at the start of these khipu represented the place identifier, or toponym, "Puruchuco." We suggest that any khipu moving within the state administrative system bearing an initial arrangement of three figure-eight knots would have been immediately recognizable to Inka administrators as an account pertaining to the palace of Puruchuco.

Why don't level I khipu bear introductory segments? Perhaps UR63 and UR73 were not intended to travel away from Puruchuco; instead, they may have been local accounts, drawn up by the resident khipukamayuq for accounting purposes within the palace. If the seven khipu in Fig. 1 register demands for service received from outside Puruchuco, meaning that if the relation among them is one of partition, then the level I khipu would have represented the reorganization of the mandate from outside in relation to the availability of resources at the local level. In this scheme, level I khipu would have pertained only to local accounting matters, and it would have been unnecessary to attach the place identifier. However, if the overall relationship is one of summation, and these khipu were prepared as a report on local conditions for dispatch outside Puruchuco, then level I khipu would represent the raw tables of local information that served as the foundation for constructing level II and III khipu. Level III khipu, the summary reports, would have been sent to a distant administrative center.

We suggest that khipu may have contrasting number qualities depending on whether they represented instructions coming from the state administration to a local accounting center or were records produced within a local accounting center with regard to existing community resources. In the first circumstance, we suspect that khipu values would have tended to be even decimal values or calculations of values in standard proportional shares. If a khipu account was compiled from within some local administrative center to be sent upward to higher level officials, counts of resources could be expected to have reflected the vagaries of the natural distribution of items in society. Such numbers are less likely to be whole and rounded or perfectly proportional.

We believe that the Puruchuco archive is the first known example indicating how information moved both up and down the Inka administrative hierarchy. There is insufficient evidence to determine whether the khipu are related through data partition or summation; however, careful study of the Puruchuco and other khipu archives may provide the foothold needed for addressing the most difficult question facing students of the Inka khipu: How did the khipu-keepers of the Inka administrative system record the identities of objects—people, animals, produce, manufactured goods, etc.—in the three-dimensional forms of their knotted-string records (*7*)?

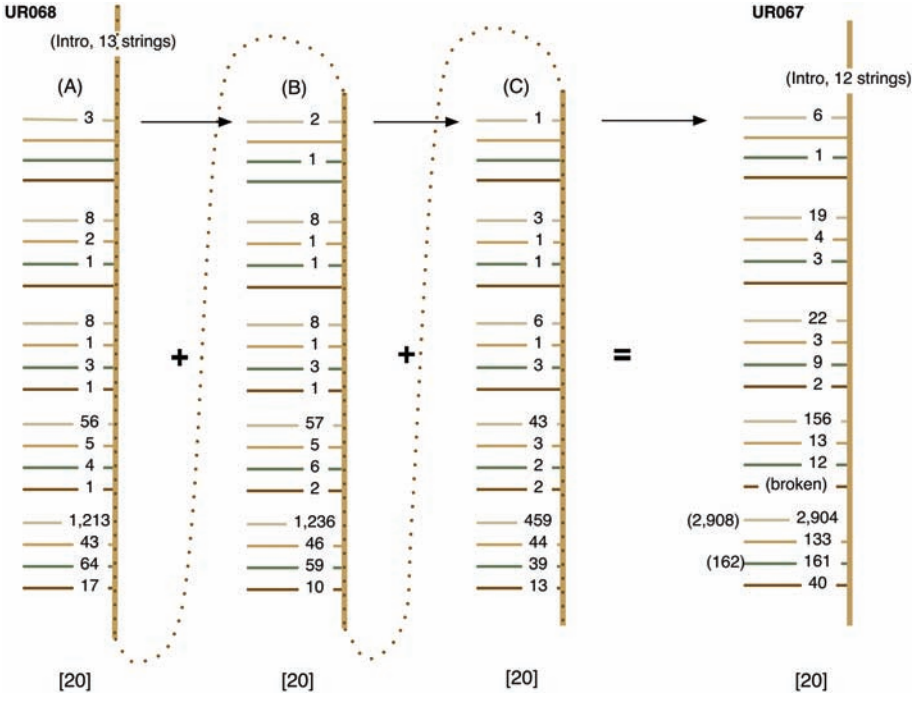

Fig. 3. Numerical and color correlations between khipu UR68 and UR67.

References and Notes

1. G. de la Vega, El Inca, *Royal Commentaries of the Incas* (Univ. of Texas Press, Austin, TX, 1966).
2. C. Mackey, thesis, University of California, Berkeley (1970).
3. Thanks to Julio Tello Solis for his transcription (10 July 2004) of the notes from the excavation field reports at Puruchuco, here translated by Urton: "9 August, 1956—The work consisted, as over the past three days, in removing 'fill,' or dirt from the upper part of sector B to fill a pit in Platform A … In the zone of extraction (Sector B, upper part) of the fill the workman Lizama encountered a narrow-necked urn (cantaro), semi-ovoid in form, covered with soot (hollín) and with an applique on the outer body in the form of a serpent; its [i.e., the urn's] mouth was covered by a small lagenaria [bottle gourd]; in the interior there were found 10 khipu of regular size, 3 of which had red/orange/yellow tassels, 11 medium sized ones, and several loose pendant strings, all in a good state of preservation."
4. Sample 9 was in the Puruchuco museum when Carol Mackey studied this collection in the 1960s. When we restudied the Puruchuco khipu archive in the summer of 2004, 9 was no longer in the collection. Museum personnel could not tell us what had become of this sample.
5. C. Radicati de Primeglio, *La 'Seriación' como posible Clave para Descifrar los Quipus Extranumerales* (Biblioteca de la Sociedad Peruana de Historia, Lima, Peru, 1964).
6. F. Salomon, *The Cord Keepers: Khipus and Cultural Life in a Peruvian Village* (Duke Univ. Press, Durham, NC, 2004), pp. 252–255.
7. The Khipu Database project, located in the Department of Anthropology, Harvard University, is described fully on the project Web site at http://khipukamayuq.fas.harvard.edu/.

8. We thank L. F. Villacorta Ostolaza and the staff of the Museo de Sitio Puruchuco–Arturo Jiménez Borja: Bullón, Díaz, and Solis. We thank NSF (grant BCS-0408324); the Dumbarton Oaks Foundation; and the Faculty of Arts and Sciences, Harvard University, for support; and the John D. and Catherine T. MacArthur Foundation for G.U.'s MacArthur Fellowship.

11 April 2005; accepted 13 July 2005